NASA Conference Publication 2119

Assessment of Carbon Fiber Electrical Effects

An industry/government briefing
held at Langley Research Center
Hampton, Virginia
December 4-5, 1979

NASA

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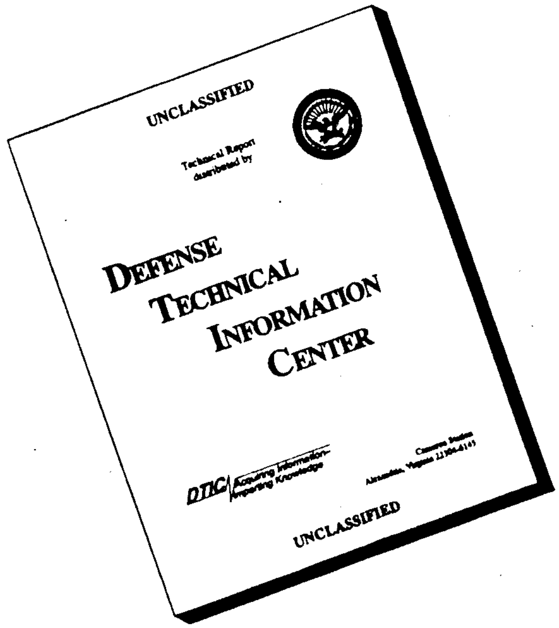

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National Aeronautics
and Space Administration

**Scientific and Technical
Information Office**

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PREFACE

This publication is a compilation of the presentations at a conference on the electrical effects associated with the accidental release of carbon fibers. This conference was held at the NASA Langley Research Center, Hampton, Virginia, on December 4 and 5, 1979.

A coordinated Federal Government action plan was announced in January 1978 to study the potential problems arising from the projected increased use of carbon-fiber composite materials in civilian applications. The primary concern was the electrical hazard associated with carbon fibers released from burning of carbon-fiber composites such as might occur in crash fires of air or ground vehicles containing carbon composites and disposal of carbon composite waste or worn-out parts. The Federal Government action plan outlined in NASA Technical Memorandum 7818, "Carbon Fiber Study" dated May 1978, assigned responsibility for various elements of the study to appropriate federal agencies. As its part of this plan, NASA Langley Research Center has assessed the risks associated with the accidental release of carbon fibers from civil aircraft and the need for protection of civil aircraft from accidentally released fibers. The results of the NASA assessment were presented at the conference. In addition, other government agencies with significant studies underway reported on the status of their efforts.

The NASA findings should be considered preliminary inasmuch as the verification test analysis was not complete at the time of the conference. A final report on the NASA risk assessment work will be submitted to the Office of Science and Technology Policy in early summer 1980.

Use of trade names or names of manufacturers in this report does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

INTRODUCTION

Carbon and graphite fibers have high strength and stiffness and are lightweight, making them very attractive for use in structural composite applications. The fibers also have high electrical conductivity such that, when free carbon fibers settle on electrical contacts, they can cause equipment malfunctions or damage. As long as the fibers are embedded in the matrix of a composite material, they pose no hazard. However, when the composite is burned such as may occur in a crash-fire accident, fibers can be released from the matrix, become airborne, and disseminate over large areas, creating a potential hazard to electrical and electronic equipment.

Because future applications of carbon based fiber composites were expected to be large, a Federal study of the potential hazard associated with their use was initiated in 1977 under the direction of the President's Office of Science and Technology Policy (Ref. 1). Since NASA has had heavy involvement in carbon fiber composite research and in the development of applications of the composites for use in civil aircraft, NASA was assigned tasks to develop alternate materials, to quantify risks to the nation associated with accidental release of carbon fibers from civil aircraft and to assess the need for protection of civil aircraft from accidentally released fibers.

The Graphite Fibers Risk Analysis Program Office of the NASA Langley Research Center has completed the latter two of the above NASA tasks. The results of the work on the tasks were presented at a briefing for industry and government on December 4 & 5, 1979. The briefing which is documented herein, also included a status report of the work done by some of the other government agencies involved in the carbon fiber studies.

An interim report on the NASA work was presented approximately a year prior to this conference and is documented in Reference 2. A final report on the NASA Langley Research Center work is scheduled for publication in early summer, 1980.

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2. Carbon Fiber Risk Analysis. NASA CP-2074, 1979.

CONTENTS

WELCOME AND PROGRAM SUMMARY

R. R. Heldenfels
NASA Langley Research Center

Welcome to the Langley Research Center. We are pleased that you are here for this briefing on the risks associated with the accidental release of carbon fibers from civil aircraft. This is the second formal report on our risk assessment activities. A similar meeting was held here on October 31-November 1, 1978, reference 1. At that meeting, we presented a status report on our program and our first comprehensive assessment of the risk. Since then, we have collected much additional data and refined our analyses. The result is that our estimate of the public risk from using carbon fibers on current and future civil aircraft in the United States is very small by any standard and can be considered negligible by some. Consequently, we plan to complete this risk assessment activity in the next few months with the publication of all of our data analyses. Today we will present those data and analyses and the conclusions we have drawn from them. In addition, similar activities by other government agencies will be described tomorrow. We will appreciate hearing your comments on the validity of our conclusions and whether any significant factors have been overlooked in our studies.

As you are aware, carbon-based fibers, often referred to interchangeably as graphite or carbon fibers, have high strength and stiffness that make them very attractive as the fibrous component of a composite material. Such composites are being used in an increasing number of applications because of their performance and cost benefits. The current and projected applications include sporting goods, automobiles, aircraft, and spacecraft in both the civil and military sectors. NASA, in particular, has conducted and sponsored extensive research and development to support the application of composite materials in civil aircraft. This NASA activity has emphasized carbon-fiber composites and it has been oriented primarily toward commercial transport applications. Significant use of carbon-fiber composites is planned in the new commercial transports now being sold.

However, because of their high electrical conductivity, free carbon fibers that may get into electrical equipment can settle on or across electrical contacts or circuits and cause equipment malfunctions or damage. Plants that manufacture or process carbon fibers have experienced such problems but have solved them easily by protection or modifying the equipment involved. As long as carbon fibers are part of a composite

material (imbedded in a matrix), they pose no known hazard. They become an electrical hazard when individual fibers are released from the composite in a crash-fire accident.

Figure 1 is a photograph of a few carbon fibers released from a fire. Note particularly the 1 mm length scale. Individual carbon fibers are very small (0.008 mm in diameter) and are very hard to see with the naked eye. They are not easy to detect and people could be unaware of their presence around electrical equipment.

A logical question is how much equipment damage has actually resulted from the accidental release of carbon fibers? The answer is very little to date. The problem was highlighted initially by the Fostoria, Ohio incident in which significant electrical power distribution failures resulted when bundles of unused, long, untwisted fibers were placed in an incinerator and these long, unburned fibers that had never been in a composite were subsequently dispersed over a large area. A few military aircraft crash fires have released carbon fibers from composite structures, but no damage to electrical equipment has been specifically traced to these or similar vehicle accidents. The Fostoria incident, which dispersed very long fibers, is not representative of the accidental release of very short fibers from aircraft accidents. It is the only known incident in which accidentally released carbon fibers have caused any damage.

However, the risk of accidental release will increase with the expected increased use of carbon fiber in both civil aircraft and other applications. Current estimates of future use of carbon fiber composites will be presented tomorrow. Because future applications were expected to be large (several million kilograms per year by 1990), a federal study of this potential hazard was conducted in 1977 under the direction of the Office of Science and Technology Policy in the Executive Office of the President.

The result of that study was reported in a press release issued by the Department of Commerce on January 20, 1978, along with a NASA publication on the observed effects of carbon/graphite fibers (reference 2). The federal action plan developed is described in another NASA publication (reference 3). Briefly, that plan assigned responsibilities to those agencies concerned with the civil use of composites in a general or specific sense. Responsibilities assigned to NASA (figure 2) were as follows:

1. Risk assessment and studies of protection of civil aircraft to be conducted at Langley.

2. Materials modifications and alternate materials research to be conducted at five NASA Centers.

3. Management support of OSTP provided by NASA Headquarters.

This meeting will not be concerned with the details of the NASA materials modification program. That program has identified ways to reduce the release of electrically conductive fibers in a variety of ways and some of these modifications may be used for other purposes in future composite materials. This program will end in 1980, too, because estimated risk is so small.

Responsibilities that were assigned to some of the other government agencies are listed on figure 3. These agencies will report on their work tomorrow in the areas of market surveys, household equipment, surface transportation, power systems, monitoring equipment and disposal.

The session today will report the results of the risk assessment activities conducted here at Langley with significant support from many organizations in government, industry, and universities. A number of laboratories in the Department of Defense have made major contributions to our program. We have examined in detail the risk from commercial transport aircraft as a source of released fibers and made an adequate assessment of the risk from general aviation as an additional source.

The question we have addressed (figure 4) is: Is the potential damage that may be created by the release of carbon fiber from civil aircraft accidents significant compared to (1) other costs of such accidents and to (2) the benefits that accrue from the use of composite materials in aircraft construction? The answer to both is no!

To get this answer we have used risk analysis methods and experimental data on the signfificant elements of those analyses. We have a series of risk assessments that define the probability of various degrees of damage from current and projected applications of composite materials in civil aircraft. This is a very complex problem. It involves the probability of occurrence of many things, such as the number and location of accidents, the amount of carbon fiber on the aircraft, how much fiber is released, how the fibers are disseminated, how far they go, what kind of equipment is in the area where the fibers are deposited, the effect of these fibers on that equipment, and the cost of equipment repair and replacement. We will describe the tests we have conducted to acquire the data needed and the analyses we have made to define the probability of various levels of risk.

An improtant consideration in our study is the character of the carbon-fiber hazard compared to other potential hazards. The carbon-fiber hazard is almost exclusively a source of

potential property damage.

We regularly experience man-caused and natural events (such as fires, explosions, earthquakes, hurricanes and tornadoes) that produce numerous fatalities and injuries each year along with many millions of dollars of property damage. The equipment and property damage from accidental release of carbon fiber will be small in comparison and fatalities or injuries will be extremely rare. Any loss of life or injuries that may result from release of carbon fibers will be a secondary consequence of an equipment failure. Our results indicate that fatalities are extremely unlikely and that there is no known health hazard from accidental release in civil aircraft accidents. In other words, exposure of people to airborne carbon fibers is not expected to harm them.

Before we give you the details of our tests and analyses today, I will summarize what we have learned, figure 5. These conclusions apply to the use of carbon-fiber composites on civil aircraft in the United States.

1. The problem is complex and much data is required to define its many facets, but we have acquired enough information to understand and scope the risks involved.

2. The amount of fibers released from civil aircraft fires is much lower than originally estimated. This is a major contribution to the low risk.

3. Equipment is much less vulnerable than originally estimated. This is another major factor in our low risk results. In many cases we found that malfunctions during a test can be eliminated by using a vacuum cleaner to remove the fibers. We learned that much electrical and electronic equipment is well protected from adverse environments, including carbon fibers, and technology is available to provide any level of protection that may be required.

4. Potential equipment damage from carbon fibers accidentally released from civil (commercial and general aviation) aircraft accidents is negligible today and is expected to be of very small magnitude in the future when carbon fiber composites are used extensively on civil aircraft. Our best estimates of the situation 15 years hence is that the expected value of equipment damage will be less than a fraction of one percent of the total cost of an aircraft accident.

5. Identified vehicle crash-fire accidents to date that involved carbon-fiber composites caused no damage attributable to the carbon fibers released from the accident.

6. Released carbon fibers do not directly contribute to fatalities and do not constitute a known health hazard.

7. The potential cost of accidental release of carbon fibers from future civil aircraft is inconsequential compared to the benefits, such as cost and energy savings, that accrue from the use of these composites.

8. We have sufficient data and analyses in hand to wrap up our investigation and publish the results in the next few months.

Our data, results, and conclusions will be presented in detail at this briefing so that you can judge for yourself the validity of our conclusions. Please tell us if you see any place where we have been unduly optimistic or pessimistic.

In conclusion, we have undertaken the difficult and complex task of assessing the risks associated with the use of carbon-fiber composites on civil aircraft. We have collected the requisite data, made appropriate analyses, and concluded that the risk is small and inconsequential. We plan to finish this project, as scheduled, with appropriate publications in a few months. If you have any relevant comments, suggestions or advice on this matter, please let us hear them before the conference is over. We appreciate your attendance and hope that you find the information presented useful in planning your future applications of carbon-fiber composites.

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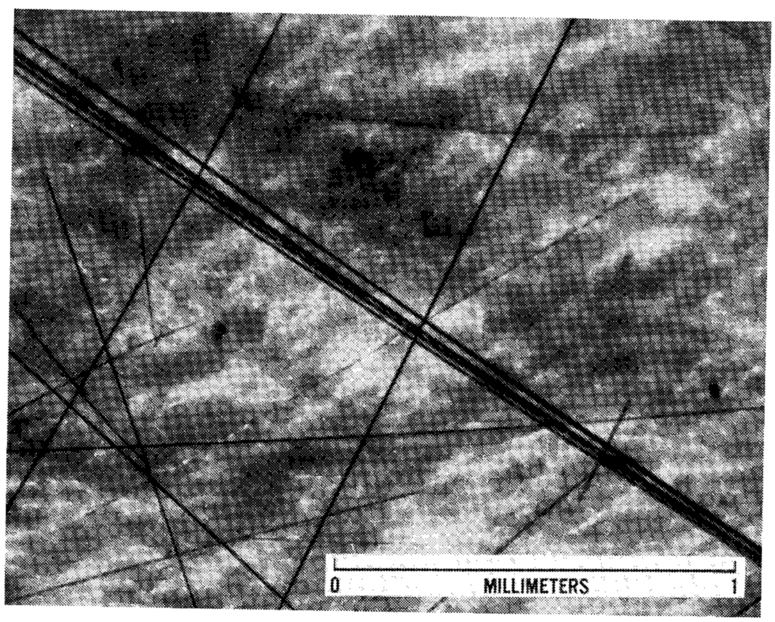

Figure 1.- Carbon fibers released in a fire.

- o RISK ASSESSMENT/AIRCRAFT PROTECTION
    - * LANGLEY RESEARCH CENTER
- o MATERIALS MODIFICATION AND ALTERNATE MATERIALS
    - * AMES RESEARCH CENTER
    - * JET PROPULSION LABORATORY
    - * LANGLEY RESEARCH CENTER
    - * LEWIS RESEARCH CENTER
    - * MARSHALL SPACE FLIGHT CENTER
- o OSTP MANAGEMENT SUPPORT
    - * NASA HEADQUARTERS

Figure 2.- Carbon fiber action plan - NASA responsibilities.

DEPARTMENT OF COMMERCE

- INFORMATION DISSEMINATION
- MARKET SURVEY
- DATA BASE MAINTENANCE
- COMMERCIAL & HOUSEHOLD EQUIPMENT

DEPARTMENT OF TRANSPORTATION

- SURFACE TRANSPORTATION
- AIRCRAFT ACCIDENT REPORTING

DEPARTMENT OF ENERGY

- POWER GENERATION, TRANSMISSION, SYSTEMS

ENVIRONMENTAL PROTECTION AGENCY

- MONITORING EQUIPMENT
- ENVIRONMENTAL STUDY
- DISPOSAL

Figure 3.- Carbon fiber action plan - selected agency responsibilities.

QUESTION: IS THE POTENTIAL DAMAGE SIGNIFICANT COMPARED TO:

- OTHER COSTS OF CIVIL AIRCRAFT ACCIDENTS?
- BENEFITS FROM CARBON FIBER USED IN CIVIL AIRCRAFT?

Figure 4.- Risk of carbon fiber release from civil aircraft.

CONCLUSIONS

- o SUFFICIENT DATA AVAILABLE TO UNDERSTAND AND SCOPE PROBLEM
- o FIBER RELEASED FROM CIVIL AIRCRAFT FIRES IS LESS THAN ORIGINAL ESTIMATES
- o EQUIPMENT VULNERABILITY MUCH LESS THAN ORIGINAL ESTIMATES
- o POTENTIAL EQUIPMENT DAMAGE VERY SMALL COMPARED TO OTHER COSTS OF ACCIDENTS
- o NO DAMAGE FROM ANY VEHICLE ACCIDENT TO DATE
- o NEGLIGIBLE RISK OF FATALITIES OR HEALTH HAZARDS
- o POTENTIAL COST OF DAMAGE SMALL COMPARED TO BENEFITS OF USE
- o PUBLICATION OF DATA, ANALYSES AND CONCLUSIONS TO COMPLETE STUDY IN A FEW MONTHS

Figure 5.- Risk of carbon fiber release from civil aircraft - conclusions.

APPROACH TO THE ASSESSMENT OF THE HAZARD

Robert J. Huston
NASA Langley Research Center

This paper is intended to provide an overview of the NASA approach to the assessment of the carbon fiber hazard. The objective of this overview is to place the later papers on the development of the data and analysis in the perspective of the entire program. I would like to point out that the first objective of the NASA program has been limited to the risk associated with accidental release of carbon fibers from civil aircraft having composite structures, that is, the potential risk to the civil sector including the general population (Figure 1). Our second objective was to assess the need for protection for civil aircraft from carbon fibers. We have identified an accident scenario for evaluation that involves crashes of civil aircraft, which in the case of large air-transport aircraft, usually occur near large airports (Figure 2). In this scenario, a burning aircraft containing carbon composites releases smoke, soot and carbon fibers to be wafted downwind from the fire and, depending upon the wind direction, have the potential of adversely impacting on transportation, manufacturing, and public service facilities as well as the home owner, commercial facilities and the power distribution systems. Another dimension of this potential hazard can be illustrated by the flow of analysis required to assess the risk (Figure 3). These are the elements that are involved in determining the risk that is associated with accidental release of carbon fiber. The subsequent papers (Figure 4) are generally organized along the lines of discussing each of these elements. The next four papers will discuss one or more of these elements either as isolated elements or combined elements. The next paper will provide a technical bridge between the laboratory and experiment evidence and the real world we are attempting to analyze. Finally, the eighth and ninth papers will show how the data and real world are combined mathematically in terms of a dollar cost impact on the U.S. economy. Dollars were chosen as the understandable common denominator measure of risk. As such it allows the addition of the costs of the failure of a single home television set with the cost of the failure of an industrial process control computer. The dollar value is more rationally understood than a statement that two electronic items failed.

Considering each element in turn, our third paper, presented by Dr. Bell, will discuss the source of the carbon fiber (Figure 5). Because carbon composites are not in widespread use today the first question we had to address is what is the future growth of carbon composites? We attack this problem by looking at the potential for various applications in the civil aircraft fleet. We found that general aviation, at this point in time, has only a single aircraft in production that uses carbon composite. That aircraft, a helicopter using less than 50 kg of carbon fiber, has only been in production a short time and current orders are only now approaching the 300 level. There is one airplane under construction and another in a preproduction stage which utilizes carbon composites. The viability of these two ventures is not yet proven. Both of these aircraft are turbine powered executive aircraft with a limited

potential for mass marketing. The remainder of the general aviation industry appears to be unprepared, for financial and technical reasons unrelated to the carbon fiber hazard, to begin to apply carbon composite technology to their designs. Therefore, we had to look at an industry that does not appear to be ready to adapt carbon composite applications and project the usage that they could have if they were encouraged to do so. I should point out that, for our purposes, general aviation is defined as all United States aircraft minus the air transport aircraft. That includes rotocraft, executive jet transports and the two seat trainer usually misnamed the "cub." We assumed a 30 percent a year growth in carbon fiber usage and projected the usage shown in Figure 6. Based on that projection, in about the 1993 time frame we would be looking at in excess of a million kilograms of carbon composite being flown in the general aviation fleet. Actually, that is a small amount of carbon fiber per aircraft in a very large fleet of aircraft.

In the air-transport area we took a different approach. We had the assistance of the major air-transport aircraft manufacturers in the United States. We analyzed the capability of these individual companies, considered their plans and the possibilities in which they could introduce carbon composites, and from that determined the date of various applications of carbon composites on their production aircraft for the next 15 year time period. Combining that information with an FAA study of the size of the air-transport fleet that is anticipated to be required over the next 15 years, we were able to develop the projection of carbon fiber usage on air-transport aircraft illustrated in Figure 6. The details of the 1993 estimate of air-transport fleet usage are illustrated in Figure 7. The carbon fiber usage is given as a function of the percent of the fleet exceeding a given level. We see that about 73 percent of the 1993 fleet would have some amount of carbon composite, even though it's a small amount, and one half percent of the fleet might have as much as 10,954 kilograms of carbon on the aircraft. It was this estimate of the carbon fiber usage that has been used in the analysis by Dr. Pocinki et al. (Reference 1) and Dr. Fiksel et al. (Reference 2).

In addition to the carbon fiber use projection, we have had to analyze the accident experience. The crash fire frequency is fairly easily obtained from the records of the National Transportation Safety Board (NTSB). However, that data is not completely adequate to determine the degree of damage involved. Many accidents that are listed as fire accidents in the NTSB data did not involve significant damage to the aircraft. In order to understand this area quite well, we had Boeing, Lockheed and Douglas analyze all of the jet transport accidents that have occurred since the jet transport was introduced. We were able to determine the magnitude of the fire damage for these accidents and determine the percentage of the various components consumed in the fire (Figure 8). The examples shown in the figure illustrate the damage to components exposures to fire as a function of the percent of accidents with fire. The rudder, for example, tends to be the least damaged component. Very rarely is a rudder totally destroyed and in most accidents it is only partially consumed. The components that are most heavily damaged are the fuselage or wing-body fairing. All other components tend to fall between the two extremes of the rudder and the fuselage.

We found that the fire dynamics and fire chemistry were not a well-understood subject. We found that we had to develop a suitable theory and obtain an experimental verification of that theory. We asked the Ames Research Center, which has been working in fire studies for a number of years, to take responsibility for development of a suitable theory and to obtain an experimental verification of the theory. As a part of that effort a series of tests were done at the NASA White Sands, New Mexico facility. Figure 9 shows one of these tests where a large pool fire was started and measurements were made in the fire at a number of elevations in the fire plume to determine fire temperatures, velocities, fuel-air ratios and other such elements that are important to understanding the potential for carbon fiber release. We used this kind of information to predict, for example, the percentage of released fiber that would be burned up in a fire plume.

Finally, we have had to quantify the composite fiber release characteristics. Dr. Bell's paper (Reference 3) discusses this in considerable detail, but let me just introduce this subject by this illustration of a sample specimen in a test chamber (Figure 10). This is a 6.35 cm by 15.24 cm (2 1/2 in. by 6 in.), 32-ply specimen in a radiant and gas-fired furnace. The illustration shows that the specimen has had layers of fiber and epoxy removed as it was gradually eroded away in the fire. In this particular series of tests, performed by AVCO, we found that as this charcoal glowing effect developed we could record with a camera the fibers being burned or oxidized away.

Considering the next elements in the flow of analysis, Dr. Elber will be discussing the areas of dissemination, redissemination and transfer function (Figure 11)(Reference 4). We had to relate the existing pollution dissemination models to carbon fiber transport. Dr. Trethewey at the Army Dugway Proving Ground had previously completed most of the experimental and theoretical work in this area and assisted us with what additional help we needed. In addition, we had to quantify the post release redissemination of carbon fiber. We again went to Dr. Trethewey at Dugway for an experimental study. Dr. Elber will discuss and interpret the results of that experiment. We have to quantify the potential for carbon fiber to be transported into buildings and into equipment. To do this, we had to develop test methods and acquire data in building and equipment transfer functions. Most of our data in this area was generated by the Army Ballistic Research Laboratory at Aberdeen or by the Bionetics Corporation using the Langley Fiber Chamber.

Our next element in the flow of analysis, equipment vulnerability, will be covered by Israel Taback in Reference 5. Once fibers have been transported through the atmosphere and into enclosures, we have to analyze the electrical effects on various equipment. In fact, we also have to identify the various types of equipment that we must consider in our analysis, and by our choice of an accident scenario, we have to consider a fairly wide range of equipment - ranging all the way from consumer products that occur in the home to aircraft components (Figure 12). Once we have identified a suitable sample, we need to conduct fiber exposure tests on these components and then analyze the results. We have at Langley a carbon fiber test chamber and we have been using similar facilities at the Army Ballistic Research Laboratory (Figure 13).

Basically, we place test specimens in an enclosed chamber. We run raw virgin fiber through a chopper, cutting the long length of fiber into prescribed short lengths of fiber, aspirate the fiber into the room and let it settle as it would in a normal atmospheric environment. Through monitoring, we determine the condition or the health of the equipment being exposed to fiber and through monitoring of the fiber concentrations and exposures, we determine the level of exposure at which failures can occur. A number of duplicate tests are required to obtain an adequate statistical sample of the failure rate. This method is used to develop data from which we can generalize for the equipment considered in the risk assessment. I should also point out that we have had to consider "failures" other than equipment malfunctions and Israel Taback will discuss, for example, the potential for shock hazard from some common, everyday equipment that you might have around your home, like a toaster. In addition to the fiber chamber test data we have utilized circuit analysis and a fiber simulator to investigate the susceptibility of equipment to fiber exposure. The National Bureau of Standards, in meeting their own responsibilities to the national carbon fiber program and to assist NASA in gathering data, has conducted extensive analysis on consumer products.

Next, in order to integrate some of the test activities and to verify the small scale tests we chose to do some large scale experiments (Figure 14). The objectives of the large scale experiments were to verify that the small chamber tests do adequately predict the fiber release characteristics and, also, to verify that the vulnerability of the equipment that we have been testing in the chamber with virgin fibers properly represents the vulnerability of equipment exposed to fire release fibers. One of these experiments that we performed was a large scale fire release of carbon fiber (Reference 6). Figure 15 is a photograph taken from about three miles away from the fire at the Dugway Proving Ground where we burned a variety of composite structural specimens containing from 32 to 50 kilograms of carbon. Through a wide range of monitoring devices and samplers, we were able to determine the fiber flux from the burning composite and the downwind depositions. One of the devices that we used to monitor the carbon fiber flux is a large Jacob's ladder, a 305 meter square rope grid carrying several hundred passive and active fiber collectors, that is supported by the two balloons shown in Figure 15. The Jacob's ladder is placed so that the fire plume intersects the ladder so that we can measure the flux all across that fire plume.

In addition to the outdoor tests, we have performed a large scale burn in a chamber. Figure 16 shows the Dahlgren shock tube. It has been converted to use as a fire facility to release carbon fibers from composites. We built a fire midway in its length and, through the use of exit fans on the large end, drew the fire efflux and carbon fibers through the tube across electrical equipment. The equipment exposed had been previously tested with virgin fibers and had known failure characteristics. Sufficient carbon composite was burned to release enough carbon fibers to deliberately fail the equipment. It would not be adequate to expose the equipment to carbon fiber levels that would not assure failure because that would prove nothing. We had to over-expose the equipment sufficiently to deliberately fail it. We were successful and Dick Pride will discuss that test in detail. It should be pointed out that there was no possibility of spilling of carbon fiber from the open end of

the tube because we used a water curtain at the end which we found quite effectively filtered out carbon fibers.

The seventh paper of the conference (Reference 7) will present the results of a series of surveys used to provide a variety of information necessary for assessing the public risk due to accidentally released carbon fibers. As such, the surveys become a bridge between the technical and laboratory data gathered on carbon fiber release, penetration, and vulnerability effects and the economic impact of these factors. The surveys were completed as a team effort. The surveys are not the results of one company or one organizational study. A. D. Little and ORI, which performed the risk calculations, found it necessary to tie the data available in census information to real installations. We used ORI, A. D. Little and the Bionetics Corporation, as well as our Langley staff, to survey a variety of installations that ranged all the way from public facilities, utilities, commercial to industrial facilities. This report was prepared by Ansel Butterfield of the Bionetics Corporation. In each installation the teams searched for the data that we needed to tie together our modeling problem (Figure 17). We had to acquire economic data and we had to search for the sensitivity areas that might involve life critical and emergency services. In addition we had to evaluate the protection afforded in-place operating equipment. Of course, the purpose of all this was to incorporate the survey result into our analysis model so that we would have a better tie between the theoretical calculations and the real economic environment that we are trying to simulate.

The next two papers will present the results of two studies performed independently by ORI Incorporated and A. D. Little Incorporated (References 1 and 2). One advantage offered by performing two independent studies is that different technical approaches, both considered a priori credible, may be compared. If either approach is faulty, for whatever reason, significant differences in the final analysis result will occur. For this introduction, I will emphasize the similarities in the basic approach used by both groups, though A. D. Little will present the results of a completely different approach for comparison (Figure 18). The basic approach is to simulate a single accident in the scenarios under question and compute the probabilities that are associated with the accident location and condition, determine the release characteristics, that is how much fiber is released, and compute the dispersion of that fiber through the atmosphere. The simulation is based on real localities where we can determine the type of equipment that would be exposed. Based on the level of exposure and the failure rate of the exposed equipment, the computation then determines the economic consequence. Now doing this calculation once gives you a sample answer but it does not address the total probability to the entire country. And so, therefore, we must repeat this simulation sufficient times to obtain a statistically significant answer. Now the approaches of the individual contractors are different, in detail, particularly with regard to assessing the economic consequence, but basically they follow this overall approach. In one case the simulation is performed for the nine major traffic airports in the United States and is extrapolated to the nation as a whole. In the other case, the simulation is performed for the 26 airports with the highest traffic volume and then extrapolated to the Unites States as a whole.

Finally, in the tenth paper, this author will attempt to put the NASA study results in perspective (Reference 8). A number of conservative assumptions will be pointed out as well as areas where we think we have some limitations on the assessment. There have been a number of implied assumptions that you may not have recognized and some conclusions that we have not put into the main discussion that will be shared in this discussion.

Finally, the various participants in the NASA risk assessment program are listed in Figure 19. Alongside of each name is the principal contribution of the organization to the NASA program. The NASA Graphite Fiber Risk Analysis Program Office is grateful to the individuals of these organizations that contributed to the various papers presented at this conference.

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- QUANTIFY RISK ASSOCIATED WITH ACCIDENTAL RELEASE OF CARBON FIBERS FROM CIVIL AIRCRAFT HAVING COMPOSITE STRUCTURES

- ASSESS THE NEED FOR PROTECTION OF CIVIL AIRCRAFT TO ACCIDENTALLY RELEASED CARBON FIBER

Figure 1.- Carbon fiber hazard risk assessment - program objectives.

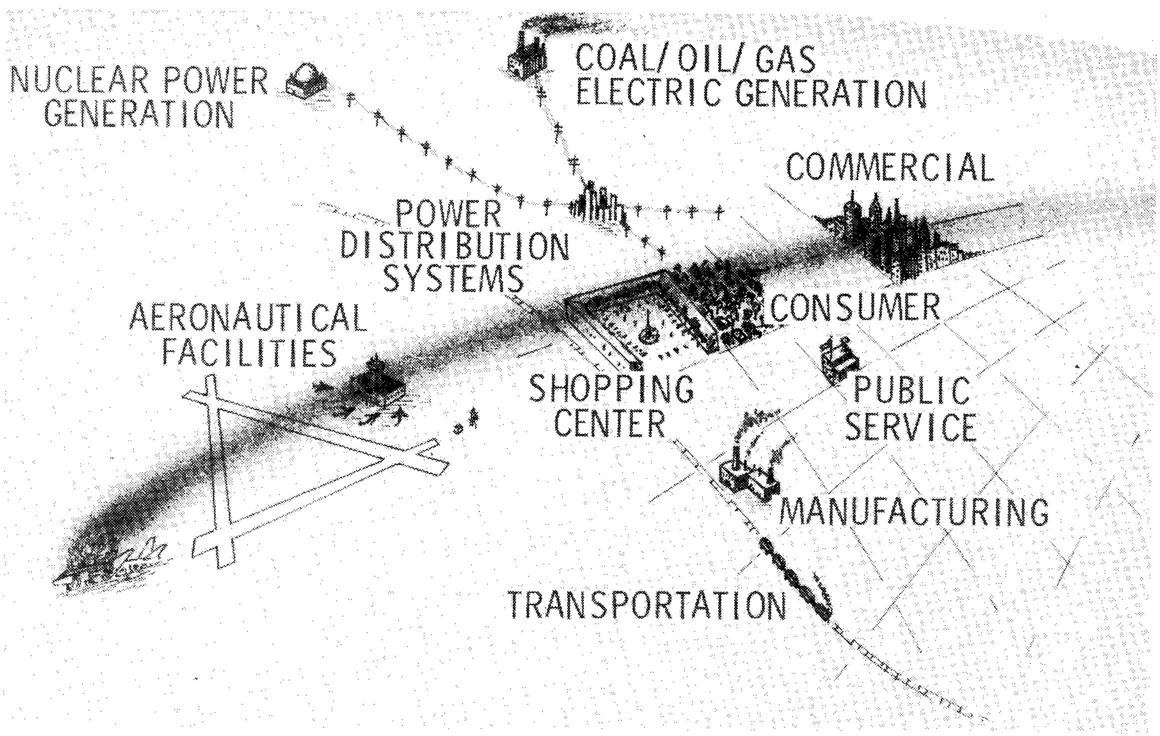


Figure 2.- The carbon fiber hazard potential.

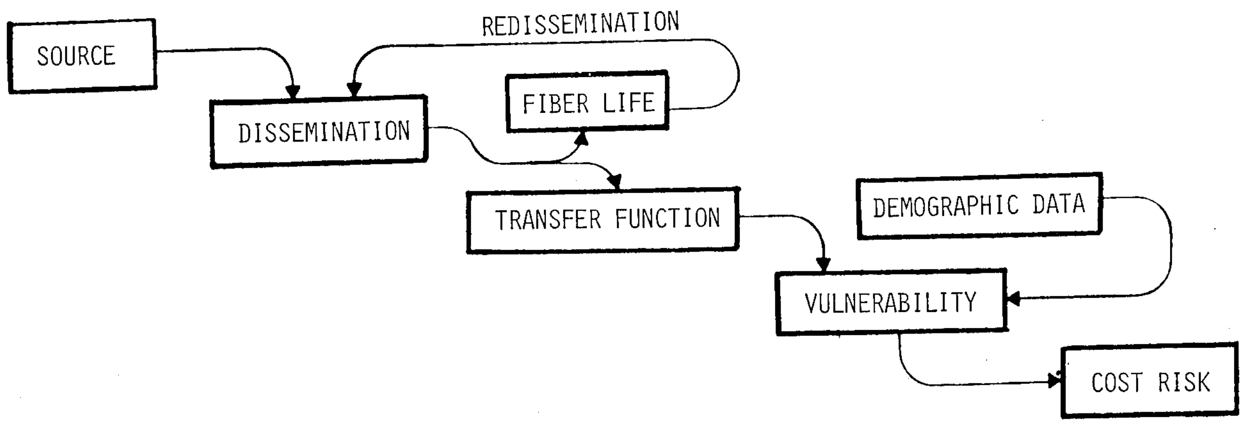


Figure 3.- Risk analysis flow.

SOURCE OF RELEASED FIBERS	DR. V. L. BELL
DISSEMINATION, REDISSEMINATION, AND TRANSFER FUNCTIONS FOR RELEASED FIBERS	DR. W. ELBER
EQUIPMENT VULNERABILITY, ANALYSIS AND TESTS	I. TABACK
LARGE-SCALE FIBER RELEASE AND EQUIPMENT EXPOSURE EXPERIMENTS	R. A. PRIDE
SURVEY OF INDUSTRIAL, BUSINESS AND PUBLIC FACILITIES TO ESTABLISH FIBER INDUCED FAILURE CONSEQUENCE	A. J. BUTTERFIELD
AN ASSESSMENT OF THE RISK DUE TO THE RELEASE OF CF FROM CIVIL AIRCRAFT ACCIDENTS	DR. L. POCINKI
AN ASSESSMENT OF RISK DUE TO THE USE OF CARBON FIBER COMPOSITES IN COMMERCIAL AND GENERAL AVIATION USE	DR. JOSEPH FIKSEL D. B. ROSENFIELD
PERSPECTIVE	R. J. HUSTON

Figure 4.- Carbon fiber hazard - NASA assessment of the risk from the accidental release of carbon fibers from civil aircraft.

PROJECT CF USAGE OVER THE NEXT 15 YEARS

ANALYZE ACCIDENT EXPERIENCE

CRASH/FIRE FREQUENCY

CRASH/FIRE DAMAGE

UNDERSTAND FIRE DYNAMICS AND CHEMISTRY

QUANTIFY COMPOSITE FIBER RELEASE CHARACTERISTICS

Figure 5.- Source.

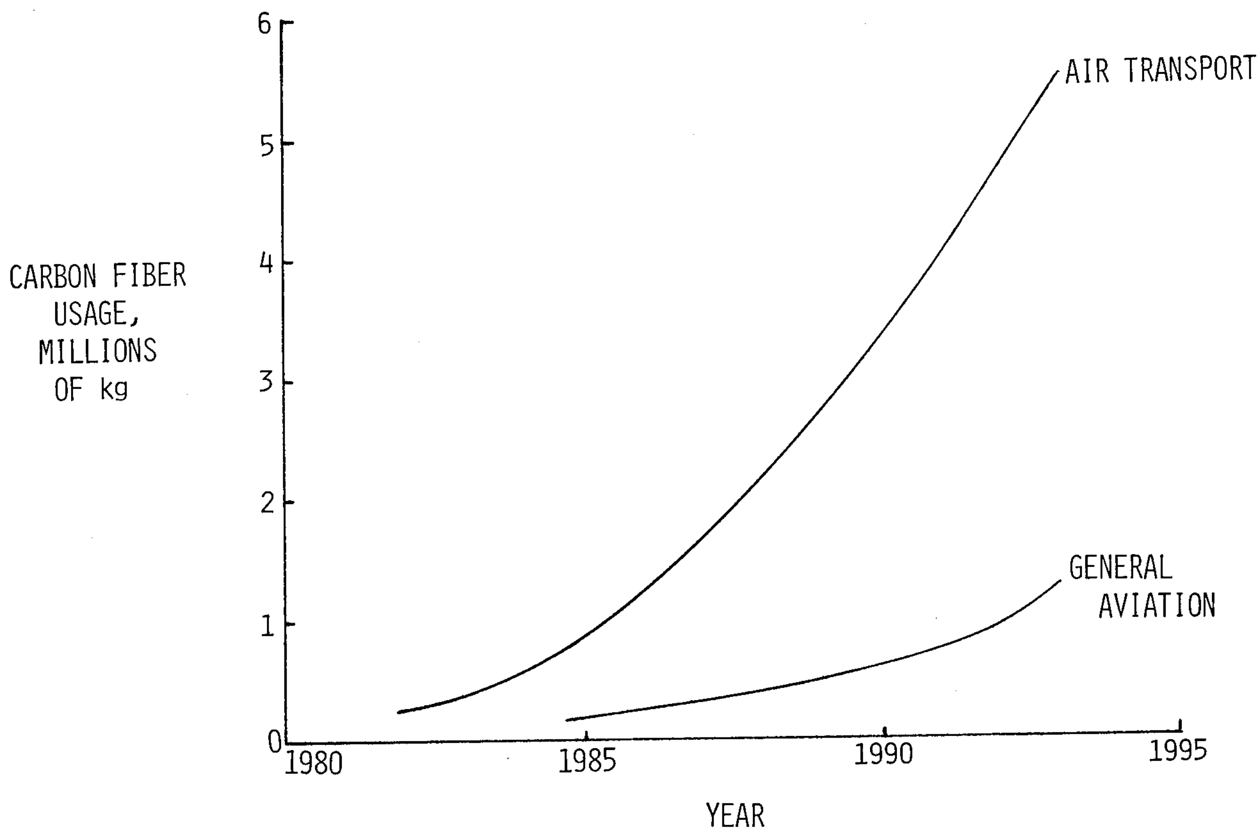


Figure 6.- Civil aircraft CF usage projection.

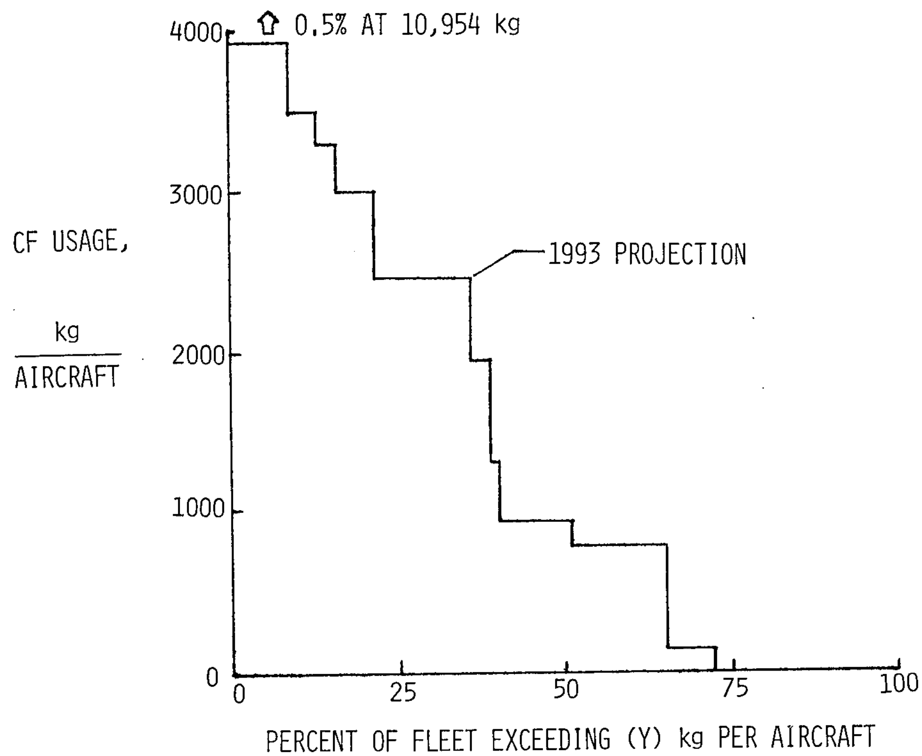


Figure 7.- Air transport fleet CF usage.

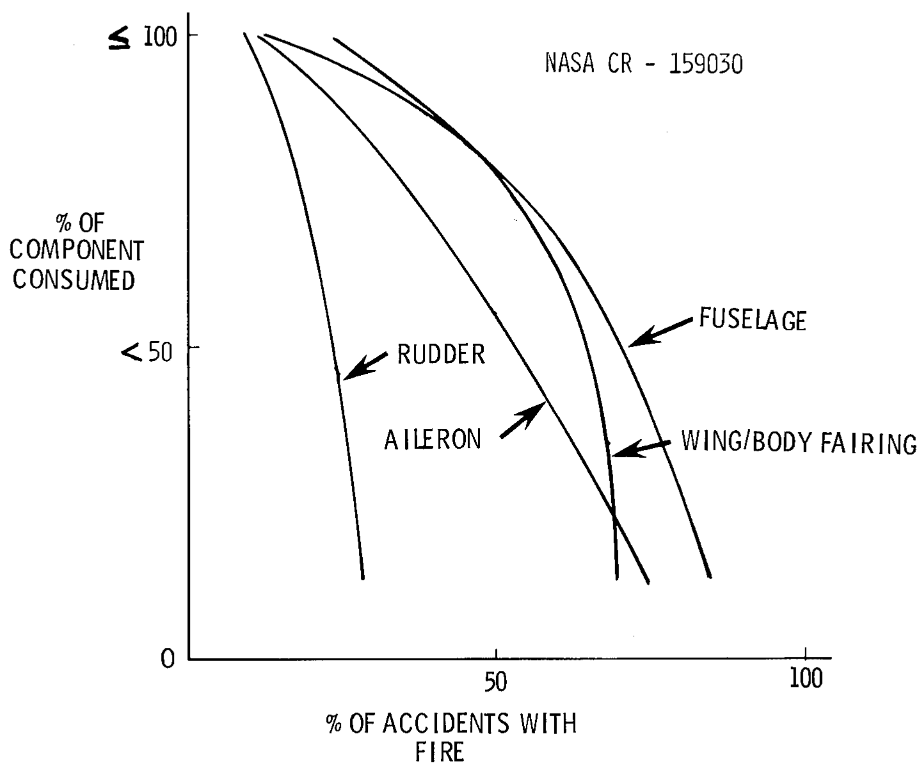


Figure 8.- Frequency of fire damage for 88 accidents (examples).

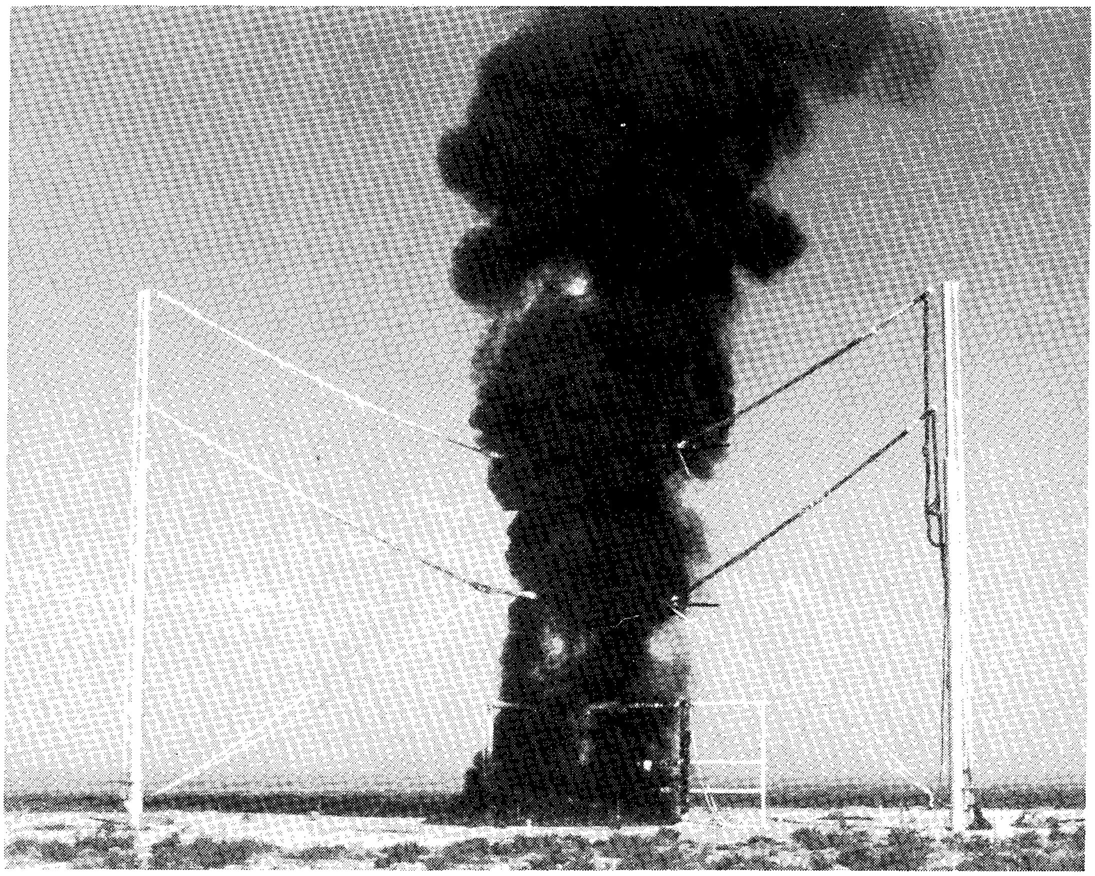


Figure 9.- Fire plume model verification tests at White Sands, New Mexico.

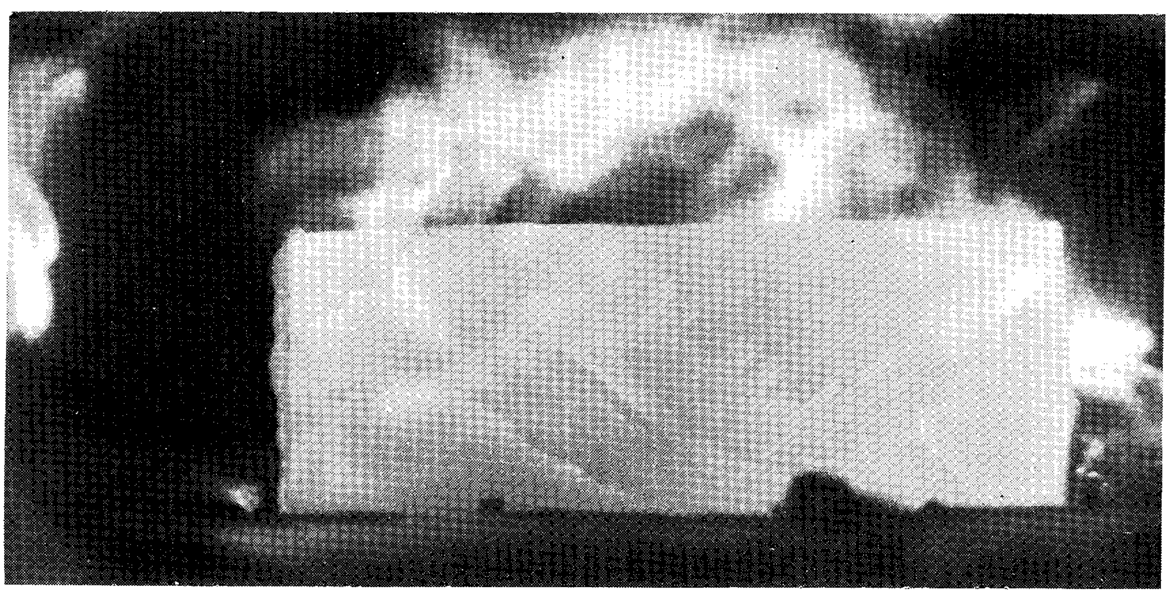


Figure 10.- Test specimen.

RELATE EXISTING POLLUTION DISSEMINATION MODELS TO CF TRANSPORT

QUANTIFY POST RELEASE REDISSEMINATION OF CARBON FIBER

QUANTIFY BUILDING AND EQUIPMENT TRANSFER FUNCTIONS AND PENTRATION FACTORS

Figure 11.- Dissemination, redissemination, transfer function.

IDENTIFY AND TEST REPRESENTATIVE SAMPLES OF EQUIPMENT

CONSUMER PRODUCTS

INDUSTRY

BUSINESS

AIRCRAFT

ANALYZE TEST RESULTS AND GENERALIZE FOR THE RISK ANALYSIS

Figure 12.- Vulnerability.

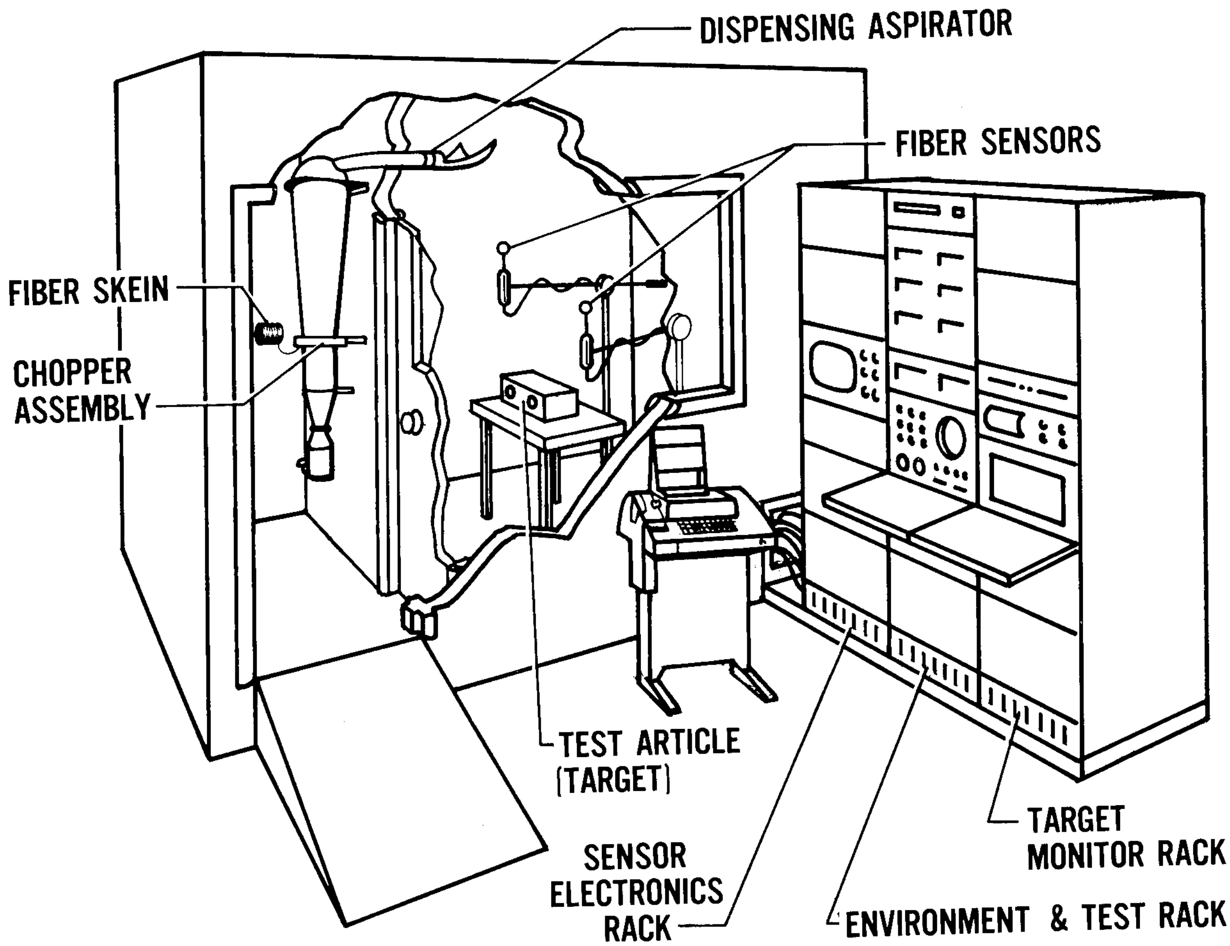


Figure 13.- Langley carbon fiber test chamber.

VERIFY THAT FIBER RELEASE CHARACTERISTICS ARE ADEQUATELY ESTIMATED BY SMALL-SCALE TEST RESULTS

VERIFY VULNERABILITY OF EQUIPMENT TO FIRE RELEASED FIBERS

Figure 14.- Large-scale experiments.

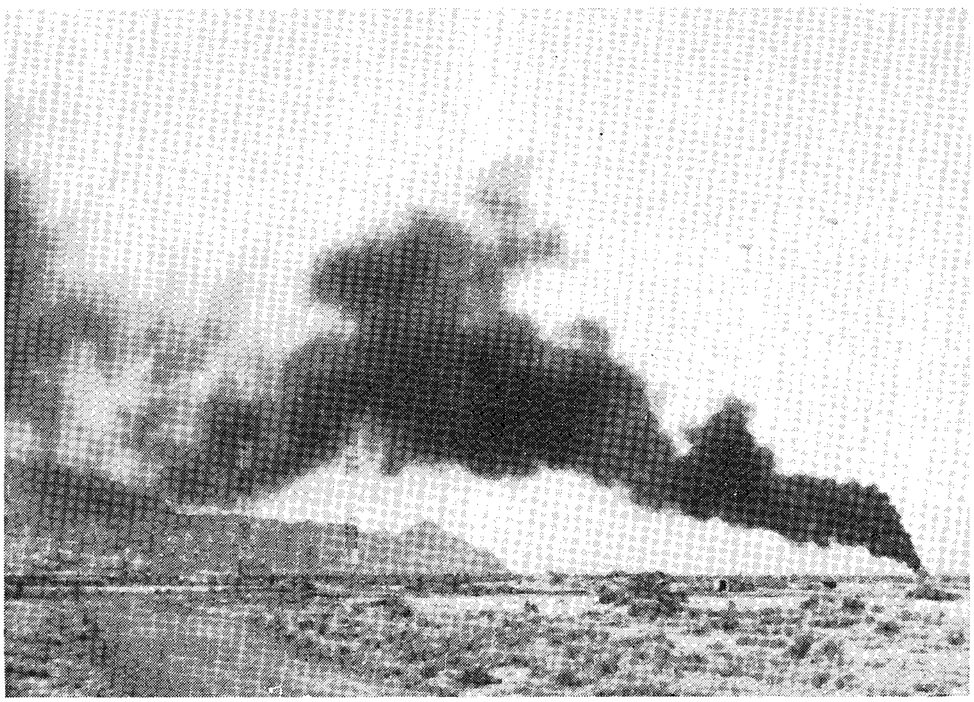


Figure 15.- Fire at Dugway Proving Ground.

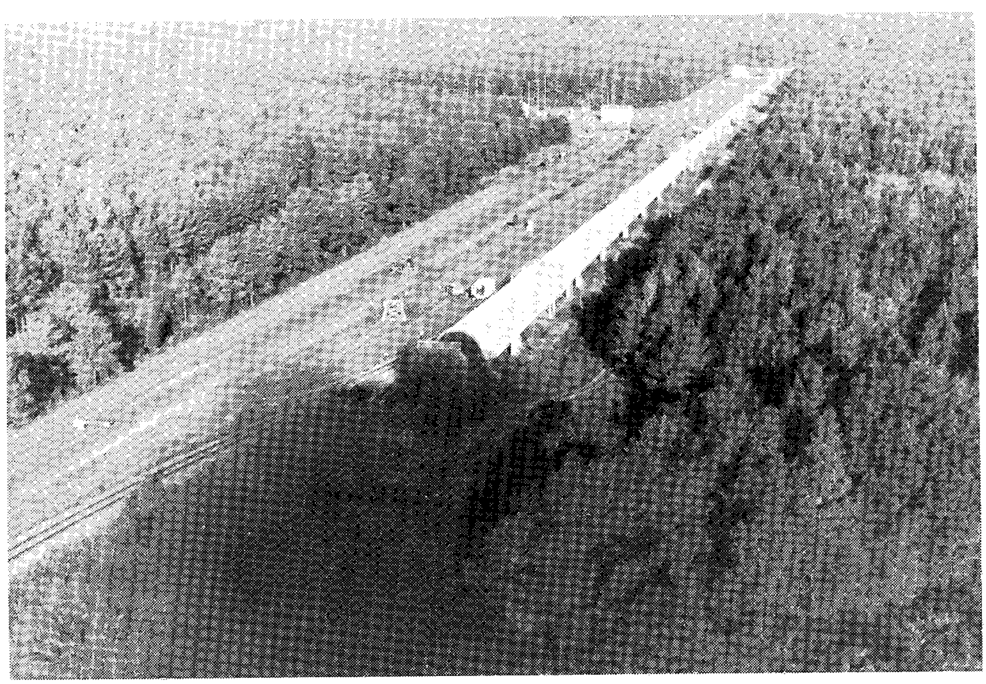


Figure 16.- Dahlgren "shock tube" burn test.

SCOPE OF SURVEYS

- 62 SURVEYS OF PUBLIC, UTILITY, COMMERCIAL, AND INDUSTRIAL INSTALLATIONS

PURPOSE

- ACQUIRE DATA FOR USE IN ECONOMIC MODELING
- IDENTIFY SENSITIVITY TO AIRBORNE CARBON FIBERS OF:

  LIFE CRITICAL OR EMERGENCY SERVICES

  IN-PLACE OPERATING EQUIPMENT
- INCORPORATE SURVEY RESULTS IN ANALYSIS MODELS

Figure 17.- Survey of facilities.

SIMULATE SINGLE ACCIDENT IN SCENARIO UNDER QUESTION

- COMPUTE ACCIDENT CONDITIONS AND PROBABILITIES
- DETERMINE CARBON FIBER RELEASE CONDITIONS
- CALCULATE CARBON FIBER DISPERSION FOOTPRINTS
- ENUMERATE EXPOSED EQUIPMENT
- DETERMINE EXPECTED LOSSES

REPEAT SIMULATION SUFFICIENT TIMES TO OBTAIN STATISTICALLY SIGNIFICANT ANSWER

Figure 18.- Risk computation - overall approach.

AIR FORCE GEOPHYSICS LABORATORY	- LARGE-SCALE TESTS
AMES RESEARCH CENTER	- FIRE DYNAMICS AND CHEMISTRY
SCIENCE APPLICATIONS, INC	- THEORY DEVELOPMENT
WHITE SANDS TEST RANGE	- FIRE MEASUREMENTS
AVCO	- SOURCE
BALLISTICS RESEARCH LABORATORY ABERDEEN	- VULNERABILITY, TRANSFER FUNCTION
BIONETICS CORPORATION	- PATHFINDER STUDIES, VULNERABILITY, SURVEYS
BOEING DOUGLAS LOCKHEED	- SOURCE, AIRCRAFT VULNERABILITY AIRCRAFT OPERATIONAL SURVEYS
DAHLGREN, NAVAL SURFACE WEAPONS CENTER	- SOURCE, LARGE-SCALE TESTS
DUGWAY PROVING GROUND	- DISSEMINATION, REDISSEMINATION, LARGE-SCALE TESTS
JET PROPULSION LABORATORY	- INSTRUMENTATION
A. D. LITTLE ORI GEORGE WASHINGTON UNIVERSITY	- ANALYSIS METHODS, SURVEYS, RISK COMPUTATIONS
NATIONAL BUREAU OF STANDARDS	- VULNERABILITY
TRW	- DATA ANALYSIS, LARGE-SCALE TESTS

Figure 19.- NASA carbon fibers risk assessment - program participants.

RELEASE OF CARBON FIBERS FROM BURNING COMPOSITES

Vernon L. Bell
NASA Langley Research Center

The first of the elements in our plan to work the carbon fiber risk analysis is the source of the fiber itself. At the first conference a little more than a year ago, our knowledge of just how much fiber might be released from the crash and ensuing fire of a composite-carrying airplane was rather shaky, at best. As noted in Figure 1, we did have some quantitative results, mostly using the Navy-developed test involving the burning of composite pieces followed by the explosive destruction of the burned composite residue, but the results of that test using portions of 737 spoilers and DC-10 rudders varied widely from specimen to specimen. However, we did come up with weighted averages for all tests of 12% and 10% single fiber release, respectively, for the spoiler and rudder. Nevertheless, no one was at all satisfied with the burn plus explosive test sequence as a valid scenario for the events to be expected in the crash of a commercial airliner. We were just beginning to acquire some results, courtesy of NASA-Ames' Redwood City contract test facility, which suggested that single fiber release might be much, much lower for more realistic means of disturbing the burned composite residue. We also knew that the forms of fibers which were released were varied, but we decided to concentrate on single fibers as the most likely form of fiber to constitute a long distance threat, if indeed a threat could exist. We had also just begun to find out that the fire-generated fibers were much shorter than had earlier been supposed, a finding which was a bright spot on the horizon of vulnerability. And then, too, we had begun to suspect that the oft-quoted "indestructibility" of graphite fibers was not necessarily true for the carbon fibers in most common use today. We believed that an undetermined amount of the fibers could be completely consumed in real life fires. Based on the earliest release data, O.R.I. (one of the contractors performing the risk analysis) was using 20% as the amount of single fiber from aircraft crash fires. A.D. Little was using two numbers: 5% for fires without explosions and 25% for fires with subsequent explosions.

Figure 2 lists the principal test facilities for the generation of the fiber release data which is given in this report. The lion's share of the laboratory work was done in the Navy's Dahlgren environmental chamber, with added support from the Scientific Services, Inc. facility at Redwood City, California, under the sponsorship of NASA's Ames Research Center. An excellent study of the fundamentals of composite fires was performed in AVCO's fire test facility. Of the three demonstration

test activities, I have only reported on that which TRW's Defense and Space Systems Group conducted for the Air Force at the Naval Surface Weapons Center, China Lake, California since NASA Langley sponsored the data reduction and analysis from those tests. Dick Pride will discuss the results from the Navy's shock tube fire facility at Dahlgren and the Army's Dugway Proving Ground.

Before showing the fiber release data, a word of explanation is in order regarding how we have measured and calculated most of the single fiber release (Figure 3). The data I shall present was acquired, for the most part, by passive instrumentation means, especially by the settling of fibers onto 15.2 x 22.9 cm (6 x 9 in.) sheets of transparent films coated with a very sticky adhesive. Sometimes fibers in a horizontal airflow mode are trapped by encountering cylinders made by rolling up sticky Mylar film. A third general technique traps fibers in a horizontal flow mode onto a bridal veil filter, usually with about 1 mm or less mesh size, coated with a sticky substance. After the deposited or trapped fibers are counted and a mean length determined, a total number of fibers given off is calculated based on the area sampled. From that total number, the mean length, and the density of carbon fibers, a total weight of single fibers released is computed. A percentage of the total carbon fiber initially present (not burned away) can then be calculated. So the number which I will generally present to you will be the weight percent of single fibers released, based on the initial weight originally present in the composite. The risk analyses to be presented later use that weight percent to determine the single fibers of a spectrum of lengths which can be predicted to be released from commercial aircraft crashes.

With that introduction behind us, I would now like to present the total results of our very comprehensive carbon fiber release test program which has been conducted over the past couple of years. I will then go into the detail of each separate piece of that program, which I hope will leave you convinced that we have a pretty good handle on how much potentially hazardous carbon fiber can be expected to be released from the total representation of an aircraft crash fire. I will first present the data in terms of the amount of fiber which could be released from fires, then give some characteristics of fire-released fibers, and finally tell you how we have utilized the data.

As I mentioned earlier, most of our early data came from a burn plus subsequent explosive destruction of the fibrous residue. The explosive destruction of the residual burned composite naturally leads to a large release of fiber. In some of our tests, the amount of explosive, 56.7 g (2 oz), was equal to the amount of carbon fiber present in the sample, simply because the explosive was held constant for each test, regardless of the specimen size or configuration. Although there may be crash/fire situations

involving military aircraft where a 226.8 kg (500 lb) bomb can act on 500 lb of carbon fiber in the plane, the whole idea of the explosive is admittedly unacceptable for the civilian aircraft test situation. Nevertheless, we acquired that sort of data and we are using it as the upper limit for fiber release possibilities.

So let me show you the results of the burn/explosion test on some prototype aircraft parts in Figure 4. As you can see, simple flat plates tested under the same conditions as the parts gave very low fiber release, as did an experimental turbine fan blade with polyimide resin from NASA's Lewis Research Center. A 5% release resulted from a honeycomb panel using Nomex honeycomb core between two-ply skins of carbon/epoxy tape, with an outer ply of glass fabric. (I'll have more to say about this piece of structure later). And then lastly, we have the DC-10 rudder and 737 spoiler test results which were mentioned previously. The results shown here reflect the refinements in Dugway's statistical counting procedure, leading to the present fiber release numbers of 4.1 and 5.5% for the rudder and spoiler tests.

Some data has been presented in Figure 5 which reflects the other extreme for fiber release: that given off when composites or fiber materials are burned quiescently without intentional disturbance of the fibrous residues. The specimens were burned for 20 minutes with the propane burner used in the Navy's Dahlgren Chamber. The amounts of single fibers released from three particular 737 spoiler pieces are at least three orders of magnitude less than the amounts which were released from the very same specimens which were burned and then exploded. The same vast difference between burn alone and burn plus explosion was found for the fiberglass/carbon/Nomex honeycomb paneling material which I mentioned earlier. Also shown in this figure are the low release amounts obtained by simply burning 0.45 kg. (1-pound) spools of virgin T-300 and HMS carbon fiber. Interesting, but not altogether unexpected, was the observation that after the flame was extinguished following the 20-minute burn period, the mass of T-300 fiber continued to glow for more than 90 minutes, resulting in over 90% mass loss of the fiber by oxidation. Such was not the case for the more "graphitized" HMS fiber which had virtually no mass loss. Since carbon fiber is generally manufactured, transported, and utilized on spools, this data should alleviate considerably any fears concerning warehouse, truck, and industrial fires involving virgin fiber.

The fiber release numbers for the NASA flat plates in the last figure came from a series of tests which were meant to determine the effects of composite configuration, both thickness and lay-up method, on fiber release. The results of that study shown in Figure 6 were somewhat confusing to us, since for both the burn only and the burn/explode tests, the 3.2 millimeter (1/8 inch) thick plates gave off much greater amounts of single fiber than

did the thinner and thicker specimens. However, these test specimens which were fabricated in-house at Langley, had been analyzed and QC'd very thoroughly by Robert Jewell. When we examined that back-up data, it was found that all of the test panels, except for the 3.2 mm (1/8 inch) cross-plied panel, had respectable resin contents of 30-35%. But the 1/8 inch cross-plied panel had a resin content of only 26 percent, and the C-scan analysis showed it to be porous. We believe that the lack of sufficient resin to thoroughly saturate the bundles of fibers could well have led to the abnormally high single fiber release values for the 1/8 inch specimens, since the usual fiber-holding char from the epoxy resin would be lacking in the porous portions of the composite plates. So for the first time, we suggest that the quality of composites could have a significant effect upon fiber release. Yet, it is probably safe to say that the stringent quality control procedures exercised in the manufacture of aircraft composite parts would prevent such poor quality parts from being used.

One particular test series conducted by the Navy's chamber test facility employed conditions which I feel could be the most extreme to be expected in a fire situation which might act upon composite parts in a crashed commercial airliner. These results, shown in Figure 7, were obtained by burning standard flat plates for 20 minutes with a propane burner, with airflow both during and after the completion of the burn, and also with the instantaneous release of pressurized air directed at the burned composite fibrous residue. Incidentally, the materials used in the entire Dahlgren study of the effects of various types of disturbances on fiber release were carried out using 0.15 x 0.15 m (6" x 6") specimens from 0.00336 meter (0.132 inch) thick plates of crossplied AS/3501-6 composites, all cut from two 0.61 m x 1.22 m (2 ft. x 4 ft.) high quality panels. So we felt extremely confident of the constancy of the tests up through the completion of the act of burning the specimens. The first two bars in Figure 7 show that very small amounts of single fiber were released when a 5 m/sec (10 knot) flow of air was directed at the horizontal edge of the plate, either during the 20-minute burn (first bar) or for 10 minutes following the 20-minute burn. The third bar shows very little release of single fibers when a 15 m/sec (30-knot) flow of air was directed against the edge of the specimen during its 20-minute burn period. However, the reason for that result was that the 30 knot airflow simply overwhelmed the propane flame and cooled the specimen to such an extent that very little resin was consumed. So the only reliable high airflow test was the one shown by the fourth bar, where a 30 knot flow of air was directed at a 20-minute pre-burned specimen. As you can see, single fiber release was relatively high and 30 knots of inflowing air is not unreasonable for a large pool fire. The last three bars show the amounts of fiber released when pressurized quantities of air were released instanteously at 20-minute

pre-burned composite residues. The resulting velocities of air, from 135 to 470 knots, could realistically simulate such events from raging firestorms to exploding fuel tanks.

The forms of disturbance involved in fiber release testing have been roughly broken into those considered to be external in nature, including the forces caused by explosives, air blasts and airflow, and impacts; and others considered to be internal in nature. One series of tests conducted at Dahlgren was an extremely thorough evaluation of the amounts of fiber released when the burned composite residue was impacted with various shapes and weights of pendulum heads at the end of a swinging pendulum, which has been depicted in Figure 8. Duplicate tests involving each of the five pendulum heads impacting the composite residue at four different angles of impact were run. The results shown here, which prove that the amounts of single fiber released in this manner were consistently low, seem to minimize such concerns as portions of aircraft structure collapsing onto burning or burned composite parts.

Another type of test which also addressed the possibility of fiber release by means of an external impact was the drop impact test developed and used by Scientific Services, Inc. (SSI) at Redwood City, California under a contract from the NASA Ames alternate materials program. This facility, which I described a year ago, utilized a projectile of various weights falling from different heights onto a burned composite plate in a chamber which enabled a complete collection of single fibers and other fibrous fragments. The results in Figure 9 show that all drop weights and heights gave extremely small amounts of single fibers when the projectile was dropped onto burned crossplied composite specimens, and perhaps slightly higher amounts from woven composite plates. However, the use of woven carbon fabrics in the fabrication of the specimens clearly led to a marked reduction in the total amounts of fiber fragments since the projectile punched a clean hole through the burned composite residue, compared to the massive shattering caused to the crossplied panels.

Figure 10 shows the results of what I have called disruption of the composites by forces internal to the burned fibrous residue. The burned residues from the standard 20-minute burn periods were flexed to destruction and twisted as means of simulating some other possible events that could happen in the midst of an aircraft crash fire. The specimens were also vibrated at 30 cycles per second, and simply dropped from a 2.44 meter (8 foot) height. It is apparent that these disruptive forces released amounts of single carbon fibers equally as small and smaller than did the mechanical and drop impact tests. So we feel that the entire series of impact tests conducted at the Navy's Dahlgren chamber test facility should go a long way toward defining and testing most of the likely forms of disruption to the burned carbon

fiber composites.

A carbon fiber release study, complementary to those which I have just described, was performed in the AVCO fire test facility. This facility utilized a chamber using natural gas as the fuel, but it was particularly attractive for simulating the burning of composites in jet fuel fires since it had a realistic combination of radiant and convective heat fluxes. This versatile test facility was used to study a number of different fire variables, some of which have been shown in Figure 11. Variation of the fuel to air ratios from lean to rich, holding other fire properties constant, did not seem to have a marked effect upon the amounts of single fibers released, although it did have a considerable impact on the amount of fibers oxidized by the fire. However, the effect of edge restraint in reducing the amounts of fiber released was clearly demonstrated, since according to the results shown here, nearly ten times as much fiber was released from a specimen with three edges exposed to the flame as evolved from a specimen which was mounted in a metal frame. That could be a significant factor in release of fiber from shattered composite parts in a crashed aircraft. Although the AVCO facility used an airflow of up to 8 meters/second (15 knots), pulses of argon directed at the burning composite plates were used to simulate turbulent forces in a raging fire, and the results in this chart show that such gas pulses did, indeed, increase the amount of released fibers. Movies of the AVCO tests give a strong impression that the argon pulses give the fire the turbulence which is typical of pretty healthy fuel fires.

At this point, I will summarize in Figure 12, in a very general way, what we have found about the effects of disturbance of burned fibrous residue from the standpoint of importance in causing single fibers to be given off. The explosive disruption is still generally conceded to be the extreme, but near subsonic blasts of air are almost as severe. And as I have already shown, the severity of disturbance diminishes rapidly with lesser air velocities, impacts, internal disturbances, and finally, simple burning.

I would now like to leave the broad subject of amount of fiber release and tell you what we have found out about the physical characteristics of the fibers which have been released. Last year at this time we had some results from the SSI Redwood City tests, and some TRW measurements from the Air Force outdoor tests, and as I mentioned previously, those results indicated that fire-released fibers were generally much shorter than had been expected, with average lengths of 1-3 millimeters. All of the single fiber release data I have presented thus far has been for fibers over 1 millimeter in length. A general spectrum of fiber lengths over 1 millimeter in length has been given in Figure 13, and that general spectrum has been confirmed by just about all

the composite fire testing that has been done, including that by TRW at China Lake and their Capistrano Test Site, SSI at Redwood City, AVCO, and the Navy in the Dahlgren chamber and shock tube, with the variations being encompassed in the shaded portions of the bars. I hasten to add that I said "just about all" and I will describe the exceptions to you soon. The predominance of fibers shorter than 3 mm in length has a marked effect upon the susceptibility of electrical equipment to the fibers, as will be pointed out in Mr. Taback's presentation on vulnerability of equipment.

A consideration of all the lengths of carbon fibers generated in fires is quite interesting. Such a study has been made by Dr. Ben Sussholz of TRW. The results have been shown in Figure 14. Dr. Sussholz counted and measured carbon fibers from several different tests down to 5 micrometers in length, so that should give you an appreciation for what a monumental task it was. Results of three of the tests have been shown in this figure. The first one, from a burn plus explosion test conducted by TRW, shows that more than 98 weight percent of the fibers detected and counted were less than 1 millimeter in length. At a meeting of carbon fiber representatives earlier this year, I presented that number and some skepticism concerning the validity of it was expressed. Consequently, I reviewed the data and realized that CTS-3 was an unusually severe explosion since twice the usual amount of C-4 explosive was used and it was placed both above and below the burned composite. Obviously, it really powdered up the fiber. However, CTS-1 was a test closely duplicating the normal burn plus explosive tests conducted at the Navy's Dahlgren chamber, and the results of that test, shown in the center, still indicate the great majority of fibers were less than one millimeter long, and probably electrically innocuous. Even the simple burning of a 737 spoiler specimen, with no subsequent disturbance of the fibrous residue, resulted in almost three-quarters of the fibers being under 1 millimeter. This substantiates a general feeling that the most widely used carbon fibers, such as T-300, AS, etc. have some sort of flaws in the fiber which promote the burn-through of the fiber at very short intervals.

I mentioned that just about all of the testing has resulted in carbon fibers which were less than 3 mm in length. However, recent tests in the Navy's chamber at Dahlgren have given us a striking exception. One of the materials subjected to a burn plus explode sequence, the results for which were shown earlier (Figures 4 and 5), was a 9.5 mm (3/8 in.) thick panel composed of a Nomex honeycomb core bonded on both sides to a skin consisting of a single ply of glass fabric and two plies of carbon fiber tape, with the glass being on the outside of the panel. When this panel was burn-tested in several ways, the results were as shown in Figure 15. A simple burning of the panel for 20 min with no intentional disturbance resulted in very few fibers,

calculated at no more than 0.01% of the amount of carbon fiber initially present in the panel. When a post-burn current of air at 15 meters/second (30 knots) was directed at the burned fiber residue for 10 minutes, one percent of the mass of carbon fibers was released but with a mean length of nearly 10 millimeters. The 20 minute burn plus explosive destruction reported before gave a significantly larger efflux of fibers, a little over 5 percent, and they were of a mean length a little longer than those from the burn alone. Then when a sample was burned for 20 minutes and the residue was impacted with a single blast of air at 244 meters/sec (470 knots), the result was not only a high amount of release in terms of mass (8 weight percent), but the mean fiber lengths were 5.7 millimeters, or more than twice the mean for the burn alone. In both the airflow and airblast tests, there were some very long single fibers, running up to 40 and 50 millimeters. There was something very unique from the standpoint of not only the amount of fiber release (in terms of mass) from this particular test specimen, but also from the standpoint of the physical dimensions of the fibers. On the other hand, due to the longer lengths in those two tests, less fibers were actually released from the airblast test than from the burn/explode test, but they were just a great deal longer. These anomalous results may or may not be significant from the standpoint of the effect on electrical equipment. I believe this will be brought up by Mr. Taback in his presentation on vulnerability.

Throughout the source release testing program, we have wanted to get an idea of just how readily carbon fibers can be oxidized completely, since that fiber which burns up cannot be electrically hazardous. However, the temperatures considered to be representative of fuel fires, from 1150-1365 K (1600-2000^{o}F), are so high and the rate of carbon fiber oxidation in air at those temperatures is so fast that it has been extremely tough to try to study the process in the laboratory. Nevertheless, Mr. George Sykes of NASA Langley has made a good try at studying fiber oxidation at high temperatures with thermogravimetric analysis (TGA), and some of the results of that study are shown in Figure 16. Of course a large fuel fire involves not one temperature but a range of temperatures and a mixture of mostly radiative and convective heat fluxes. In this case, he settled on 1250 K as a good middle ground temperature, (which was also the highest temperature his equipment could reach), and heated the virgin fibers up to that temperature from room temperature at a rate of 375 K per minute, meaning it took almost 3 minutes to reach 1250 K. At that point, the analysis became isothermal and weight loss was computed from that point. In addition to temperature variations in a real fire, there are also wide variations in the oxygen content of the fire, and the extent of fiber oxidation will be highly dependent on the oxygen present. Therefore, he performed the isothermal TGAs for four possible oxygen levels, and the results shown in the figure give an idea of just

how rapidly AS carbon fibers could be completely oxidized away. With no oxygen present (nitrogen atmosphere), the fibers will last a long time at 1250 K. At the other extreme, in air the complete oxidation can occur in less than a minute. These data, while not answering directly our difficult question of "How much carbon fiber will be burned up in a fire?", were extremely useful for a theoretical fire modeling effort by Science Applications, Inc. (SAI), which I will describe shortly.

Whereas the Langley study was conducted by the thermogravimetric analysis of virgin fibers, another oxidation study was done by AVCO Corporation. In this case they used actual fibrous residue from single plies of burned out composites in their combined radiative-convective fire facility. The results of their study, given in Figure 17, led to two plots of fiber mass loss with time using two types of fires, fuel rich and fuel lean. As expected, mass loss is much faster with the fuel lean or air rich fire than for the fuel rich fire. For comparison, although the AVCO study was done at only 1145 K, the air curve from the Langley TGA study is overlaid for comparison and the rate of fiber weight loss closely approximates the rate of mass loss for the AVCO fuel lean fire, as it should.

One of the early studies in this program into the oxidation of carbon fibers was performed by the TRW Defense and Space Systems Group during their reduction and analysis of the results of the Air Force's China Lake outdoor fire tests. Some of their early studies which included thermogravimetric lab work as well as analysis of the outdoor composite burn tests resulted in the important conclusions shown in Figure 18. The reduction of the fiber diameters of such burned composites as the 737 spoilers represented a tremendous loss of fiber mass, and that oxidation as manifested by fiber diameter reduction was observed for other thin composites. As will be shown in the next figure, high quality, thick composites seem to show less fiber oxidation, perhaps because of the reduced specific surface area in thick composites. And lastly, TRW believed that the very process of combining virgin carbon fibers with resins into a composite and burning away the resin left certain unspecified residues on the fibers which catalyzed the oxidation of the fibers. Although we could not confirm that observation at Langley by TGA studies, the phenomenon may still be valid since an investigation at the Jet Propulsion Laboratory showed that certain metallic species could indeed cause a drastic conversion of virgin carbon fibers to combustible fibers.

A manifestation of fiber oxidation in fires involving composites is the release of carbon fibers with reduced diameters. When the fiber collection data from TRW's Capistrano test series and the China Lake outdoor burn tests were studied, they revealed another important change in the fire-generated fibers from the

unburned fibers originally in the composites. TRW found that the fibers resulting from relatively thick (6.4 mm or 1/4 inch) composite plates used in the Capistrano test (as well as in Navy burn plus explosion tests at Dahlgren) had roughly the same diameters as the initial fibers used to make up the composites. For example, Figure 19 shows that the post-test fibers from the CTS-3 test, depicted by the solid bars, have been reduced in diameter only a minor amount compared to the diameter spectrum of the pre-test fibers shown by the dotted line bars. Test CTS-3 involved burning a one square foot composite plate with a propane burner, followed by the destruction of the residue with 4 ounces of C-4 explosive. However, fibers which resulted from the burning of representative aircraft parts in jet fuel pool fires at China Lake were drastically reduced in diameter, as demonstrated by the results for the 737 spoiler fibers given in the figure. Generally, it seems that large pool fires acting on relatively thin composites lead to a substantial oxidation of the fibers to lower diameters, while use of propane burners for combustion of composites do not. However, poor quality, porous, resin-starved composites burned with relatively small, low-radiative gas fires can still produce fibers with markedly reduced diameters.

Other factors of the fire can also result in a significant reduction in fiber diameter, indicating oxidative conditions. Figure 20 shows the large amount of oxidation that occurred when two 3.2 mm (1/8 in.) thick composite specimens (AF-4 and AF-6) were burned in propane fires in the Dahlgren facility, immediately after the cessation of which a 15-meter per second (30 knot) airflow was applied to the still-smouldering residue fiber mats. The large extent of fiber oxidation is obvious from the fact that most of the fibers measured from both tests were less than 4 microns in diameter, compared to the usual 6-8 micron diameter for the virgin fibers. An important ramification of fiber diameter reduction will be addressed later in this presentation.

At the beginning of this fiber release test program, we were disappointed to find such a paucity of information about the nature of the kinds of fires which would be involved in commercial aircraft crashes. Some analytical fire modeling for methane fires had been done, but those fires were poor substitutes for the "smoky" fires created by jet fuels. Even so, experimental verification of existing codes was lacking. Mr. Joe Mansfield of NASA's Ames Research Center accepted the challenge to provide the sort of jet fuel fire and fire plume background which would enable the prediction of both the amount of fiber which could come out of a large jet fuel fire and how they would behave in the resulting fire plume, up to the region where the plume and fibers begin to form a downwind dissemination pattern. Also needed was a knowledge of those characteristics which could allow for the prediction of fiber consumption in the fire. The result was a comprehensive analytical program, with a mathematical

model developed by Science Applications, Inc., to determine the characteristics of large liquid fuel fires, including the spatial variations of such factors as the flame velocity, temperature, soot concentration, etc., as well as the manner and extent to which carbon fibers released in the lower regions of the fire are transported and consumed within the fire. Because of the shortage of actual data with which to test the mathematical model, an experimental test program involving fire temperature, velocity and chemistry measurements was conducted at the NASA White Sands facility by means of JP-4 pool fires (Figure 21), with pool diameters of 7.62 meters (25 feet) and 15.24 meters (50 feet). Typical of the results of this excellent analytical-experimental program are those shown in the next two figures.

The isothermal contours shown in Figure 22 indicate there was a small but extremely hot region in the center of the flame. However, there is a rather large region in the center with temperatures still hot enough (1400-1500 K) to burn up carbon fibers, if sufficient air was present. The plot at the right indicates that the fiber consumption model predicted up to 15-16% oxidation of single fibers released in the fire for both 7.6 and 10.7 meter (25 and 35 foot) fires, with consumption nearly complete at a height of 20-30 meters above the fire.

In Figure 23, the original SAI model predicted excessive fire temperatures. When the experimental fire chemistry sampling showed the coexistence of both fuel and oxidizer in the center of the flame, the fluctuating chemistry model shown was developed to account for the "unmixedness" of the fires, although that model gave temperatures still somewhat higher than the experimental test data from White Sands. The oxygen mass fraction sampling data at the right shows that the oxygen content of the 15 meter fire was considerably greater than predicted by the models. This was expected to lead to a higher than originally expected consumption of carbon fibers in jet fuel pool fires.

In addition to the electrical hazards, there has been an uncertainty about the possible health hazards of carbon fibers. Under the Intergovernment Action Plan, the National Institute of Occupational Safety and Health (NIOSH) was charged with the responsibility of studying the health issues of carbon fibers. However, since NASA has done the lion's share of the testing leading to fiber release, we have tried to be alert to the formation and dissemination of fibers which could in any way provide information of value to NIOSH. In addition to our interest in the fire-induced oxidation of carbon fibers as a means of getting rid of them, the partial oxidation of the fibers shown in two previous figures can lead to fibers with sufficiently small diameters to make them respirable to humans. For guidance in what dimensions for fibers and what exposure levels should be of concern, we can look at the standards for a known fiber health hazard. Those for

asbestos control have been shown in Figure 24. The concentration and exposure levels considered to be hazardous according to 1976 OSHA standards should be kept in mind throughout this conference when expected carbon fiber levels are mentioned.

Dr. Wolf Elber of NASA Langley performed a study with a scanning electron microscope of fibers which were collected on a square 0.6 mm stainless steel mesh from the sooty exhaust of burned composites in the Navy's shock tube fire facility at Dahlgren. He was able to separate nearly 600 fibers from the soot by a settling procedure in water containing detergent. The accounting of the fiber lengths versus diameters is given in Figure 25. According to the guidelines for asbestos fibers, those fibers in the shaded lower left hand region of the figure would be of such small size as to possibly be respirable, and in this case totals 37 out of 576, or about 6-1/2% of all the fibers. To put the quantity into the proper perspective, on a weight basis those fibers with the small diameters were less than one-quarter percent of all carbon fibers isolated and measured.

Similar results were obtained by Dr. Ben Sussholz of TRW who counted and measured the small diameter fibers from the two Dahlgren burn plus airflow experiments AF-4 and AF-6 (Figure 20). However, it still has to be shown whether or not there is anything at all hazardous about carbon fibers from a health standpoint.

Our present knowledge to that effect is summarized in Figure 26. As just indicated, we have found only a few carbon fibers in our test programs which were possibly of respirable size. Only one study involving the response of animals to carbon fibers is known. In that one, guinea pigs were exposed to 2.9×10^6 fibers/cubic meter for 100 hours, or a total exposure of 10^{12} fiber-sec/m^3. Only 5 carbon fibers were found in the lungs of the autopsied animals and only one fiber was intracellular. There was no indication of macrophage formation, which would be suggestive of an antagonistic response of the animals to harmful foreign matter. As far as humans are concerned, it is known that many carbon materials have been implanted without indication of problems, so it seems fairly certain that carbon is innocuous to humans from a chemical standpoint. As Mr. Pride will tell you, NIOSH personnel have been involved in our large scale composite fire tests at Dugway Proving Ground and we feel certain they are the proper researchers to follow the carbon fiber health issue.

To return to the principal objective of our carbon fiber release testing program, the next figure (Figure 27) indicates, in a general way, the overall mass balance to be expected when a composite burns up in a fire. At the right-hand side of the ledger, the greatest share of the fiber originally in the composite will

end up as some form of fibrous residue at the site of the fire and/or as oxidation products, such as water vapor, carbon oxides, and soot. However, some of the thin, single ply strips of burned composites will be transported for relatively short distances, i.e., up to a mile or so. On the other hand, we expect that from 5 to 17-18% of the total mass of carbon fiber initially present in the composite will be released as single fibers, with no more than 1 to 3½% being of concern from an electrical standpoint. (The origin of those 1 and 3½% limits will be shown in Figure 28). And lastly, something under 0.05% at most will be given off as single fibers of such dimensions to be considered respirable.

A very general summary of a great many of the carbon fiber fire release tests has been given in Figure 28. The tests have run the gamut from simple, quiet burning of composites, an event which undoubtedly would occur to some extent in the fire involving a crashed commercial airliner, all the way to fires followed by ordinance-based explosions and pressurized gas explosions. Most of the participants in the actual risk analyses adjudged 1% to be an appropriate weight percent release of carbon fiber for all non-explosive fires, while 3½% was chosen as the release number to be applied in the case of all fires with subsequent explosions. (Those two numbers are represented by the two horizontal dashed lines in the figure). We feel those numbers are extremely conservative, meaning they still represent somewhat higher amounts of single fibers being released than are felt would actually occur.

The application of the large mass of data which has been herein presented is given in Figure 29.

First, a study of commercial air transport accident records led to an opinion that 85% of the accidents with fires resulted in fires only, while 15% of the accidents had fires with explosions sometime after the onset of fire. More precisely, only 5% of the crashes with fires had explosions after 3 minutes of fire, which was considered to be the minimum time to completely consume the epoxy resins in the composite parts which could have been present. Second, a release number of 1% single fibers was chosen for aircraft fires without accompanying explosions, while 3-1/2% of the total available carbon fiber in the burned composite parts was chosen as single fiber release for those fires with explosions. And lastly, for every kilogram of carbon fibers released from a burning composite, there will be 5 billion fibers, having an exponential distribution of lengths with a 2 millimeter mean length. In addition, although the diameter of carbon fibers has a relatively minor effect on the electrical properties, the five billion fibers per kilogram were considered to have their original diameters of about 8 microns. So, as the bottom line of this program, the data shown here represents the source of carbon

fibers to be used in the final carbon fiber risk analysis.

An acknowledgement of the excellent contributions to the source release program is in order. Dr. Kenneth R. Musselman and Mr. Ted Babinsky directed and conducted the entire test program in the Navy's Dahlgren environmental chamber, the magnitude of which is apparent from the data just presented. Dr. Ben Sussholz of TRW provided a wealth of data from the China Lake tests, and deserves special praise for his timeless efforts in counting, measuring, and analyzing fiber sizes. The overwhelming job of counting the fibers from hundreds of tests was accomplished for us by Mr. John Trethewey's group at the Army's Dugway Proving Ground as a pathfinding effort, and later by various individuals with the Bionetics Corporation. Mr. Joseph Mansfield provided invaluable assistance to this program not only by the contributions of Scientific Service, Inc., but also, and especially, by his planning and direction of the pioneering fire plume modeling and experimental work performed by Science Applications, Inc. and NASA White Sands personnel. Mr. J. Glenn Alexander of the AVCO Corporation provided an excellent study on the fire parameters in the burning of composites, while Mr. George Sykes of NASA Langley contributed a valuable, necessary and long overdue study of the fundamental thermal properties of carbon fibers.

o <u>AMOUNTS</u> - DISTURBANCE APPARENTLY NEEDED FOR RELEASE

- o BURN/EXPLODE TESTS: 737 SPOILER - SINGLE TESTS: 6-40%; AVE.: 12%
  DC-10 RUDDER - SINGLE TESTS: 7-15%; AVE.: 10%
- o BURN/DROP IMPACT TESTS: < 0.1% SINGLE FIBERS (FLAT PLATES)

o <u>FIBER FORMS</u> - SINGLE FIBERS, LINT OR CLUSTERS, THIN STRIPS

o <u>FIBER SIZES</u> - FIBERS FROM FIRES ARE VERY SHORT ($\bar{L}$ < 3 MM)

o <u>OXIDIZABILITY</u> - AS, T300, CELION TYPES BURN EASIER THAN HIGH MODULUS FIBERS

o <u>RISK ANALYSIS</u> -

- o O. R. I.: 20% SINGLE FIBER
- o A. D. LITTLE: 5% SINGLE FIBER (FIRE WITH SUBSTANTIAL DAMAGE)
  25% SINGLE FIBER (FIRE PLUS EXPLOSION)

Figure 1.- Knowledge of fiber release: November, 1978.

LABORATORY TESTS

- NAVY/DAHLGREN (VA) CHAMBER
- NASA/AMES - SSI/REDWOOD CITY, CA
- AVCO CORP./LOWELL, MA

DEMONSTRATION TESTS

- NAVY/DAHLGREN SHOCK TUBE
- NASA/LANGLEY - ARMY/DUGWAY, UT
- AIR FORCE - TRW AT NWC/CHINA LAKE, CA

Figure 2.- Test facilities for fiber release.

- RELEASED FIBERS IN FALLING MODE:
  - SETTLE ONTO STICKY DEPOSITION PAPERS
- RELEASED FIBERS IN HORIZONTAL FLOW MODE:
  - ARE TRAPPED BY STICKY PAPER CYLINDERS
  - ARE TRAPPED BY STICKY MESH FILTERS
- RELEASED FIBERS COUNTED VIA OPTICAL MICROSCOPIC TECHNIQUES
  - DIRECT COUNT OF REPRESENTATIVE REGIONS
  - BUFFON NEEDLE DROP PROBABILITY METHOD
- ONLY FIBERS GREATER THAN 1 MM USED FOR FIBER RELEASE
- WEIGHT PERCENT OF FIBERS BASED ON AMOUNT OF FIBER PRESENT IN AFFECTED COMPOSITES

Figure 3.- Determination of fiber release data.

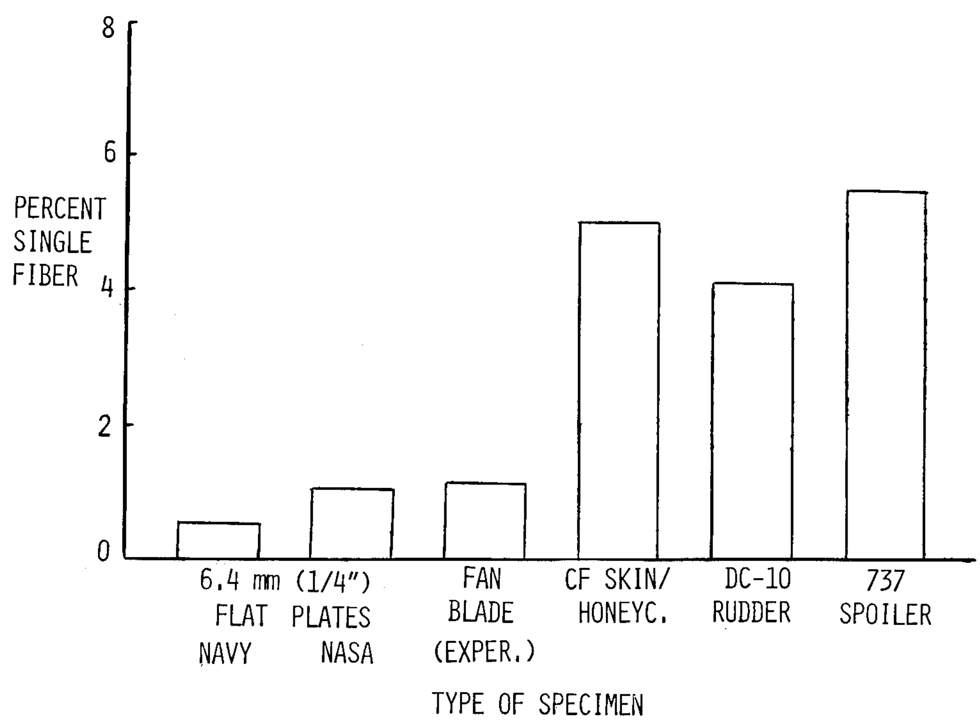


Figure 4.- Single fiber release from prototype composite aircraft parts exposed to fire plus explosives (Navy/Dahlgren chamber).

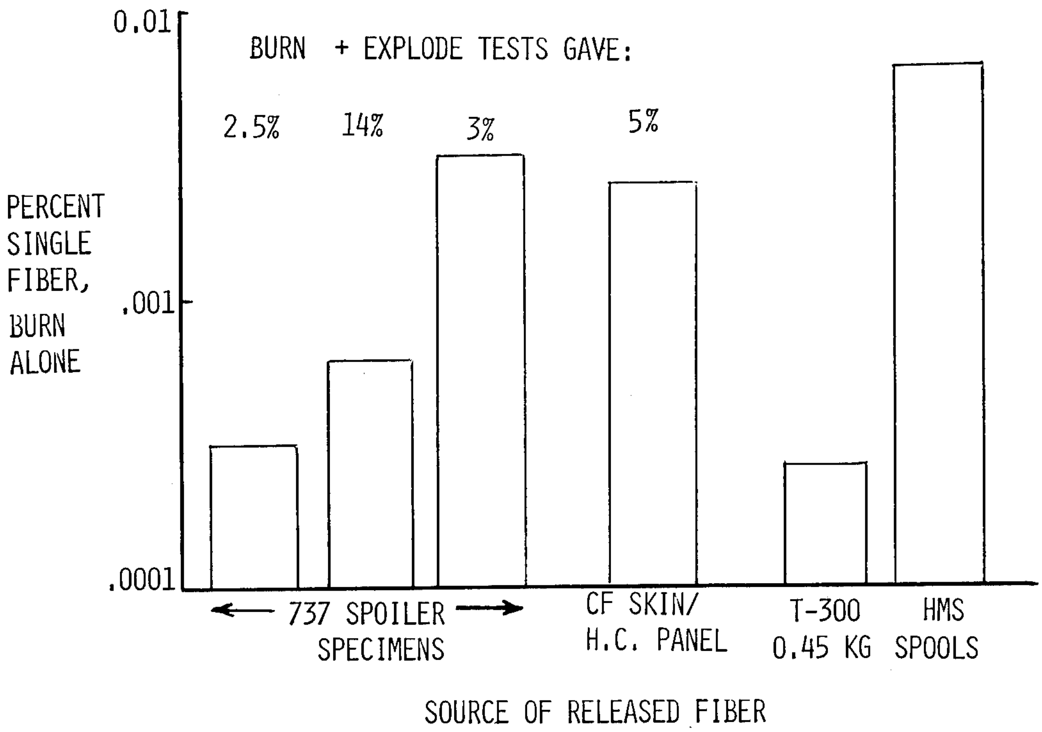


Figure 5.- Release of single fibers from propane fire vs. burn/explosive test (Navy/Dahlgren chamber).

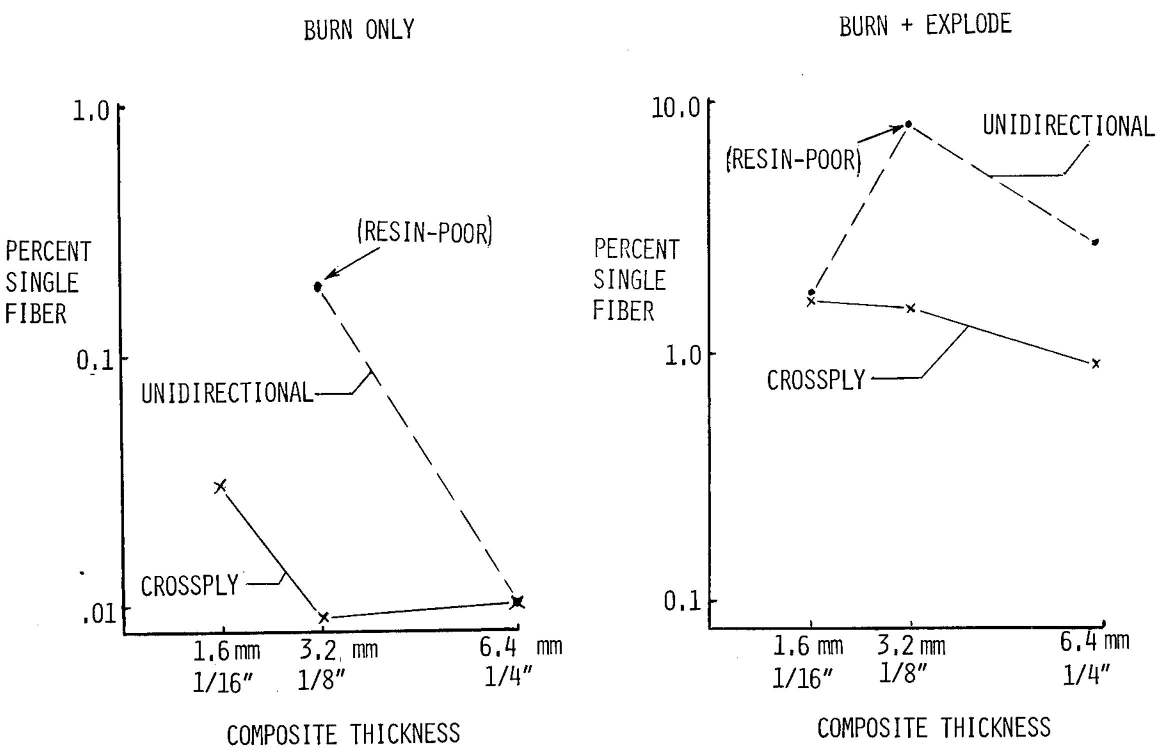


Figure 6.- Effects of composite configuration on single fiber release (Navy/Dahlgren chamber).

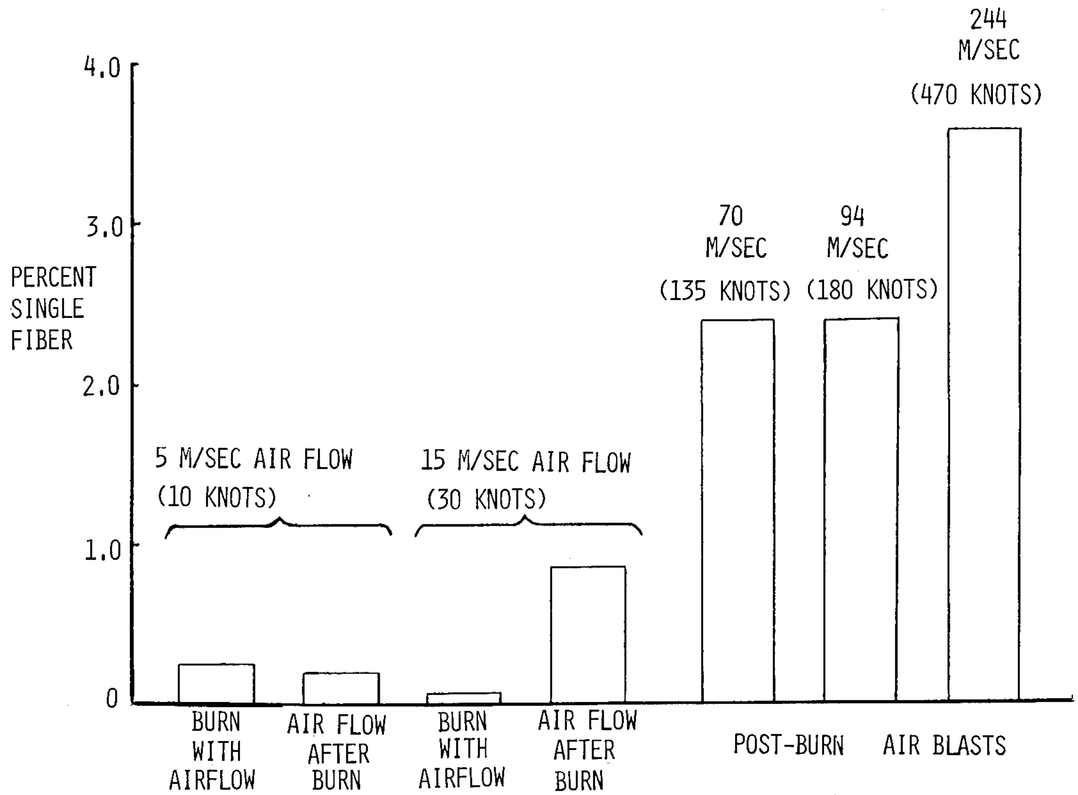
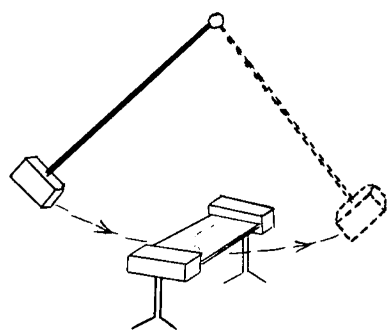


Figure 7.- Effects of low and high airflow on single fiber release (Navy/Dahlgren chamber).



TYPE OF HEAD*	% CF
ROUND, 11.4 KG	0.22
WEDGE, 11.4 KG	.11
ROUND, 5.5 KG	.04
WEDGE, 5.5 KG	.17
FLAT, 5.5 KG	.10

* IMPACT ANGLE = 90^0

IMPACT ANGLE**	% CF
0^0	0.13
45^0	.13
90^0	.22
135^0	.19

** 11.4 KG ROUND HEAD

Figure 8.- Effects of pendulum impact on single fiber release (Navy/Dahlgren chamber).

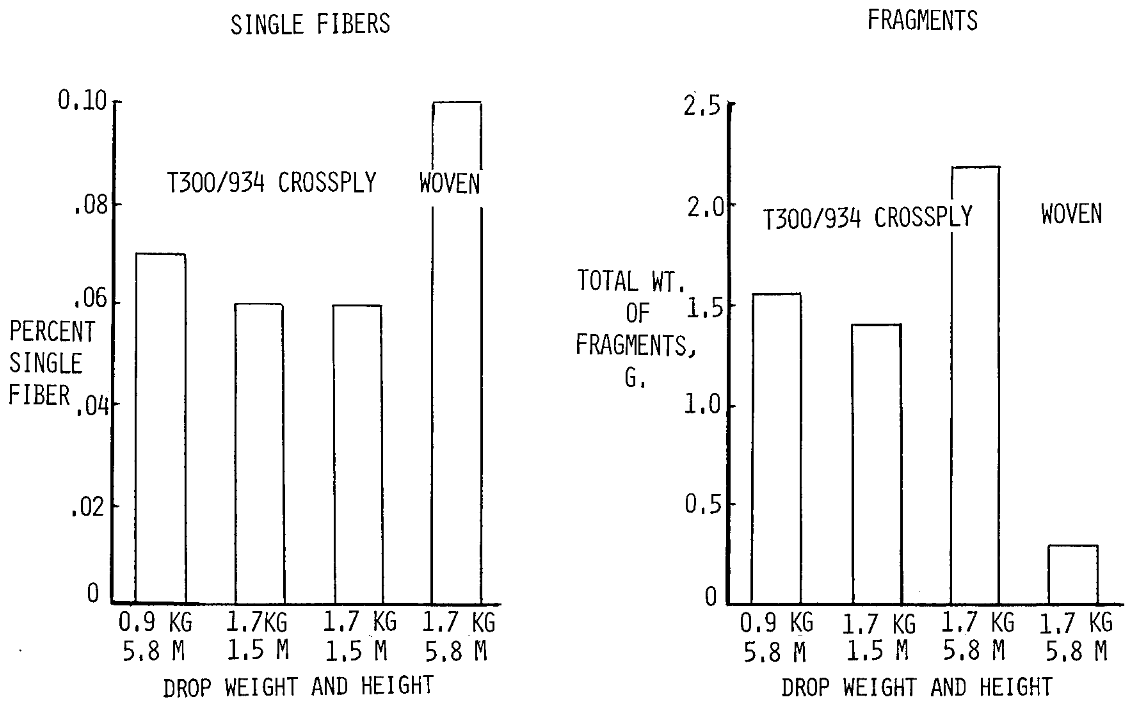


Figure 9.- Single carbon fibers and composite fragments from fire plus drop impact tests (NASA-Ames/Redwood City facility).

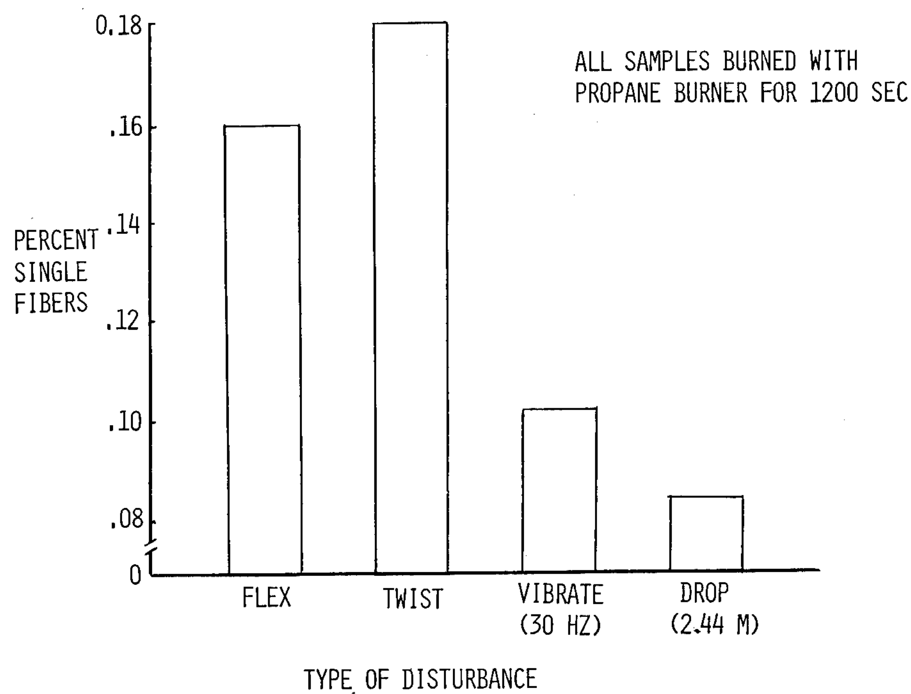


Figure 10.- Effects of internal disturbances on single fiber release (Navy/Dahlgren chamber).

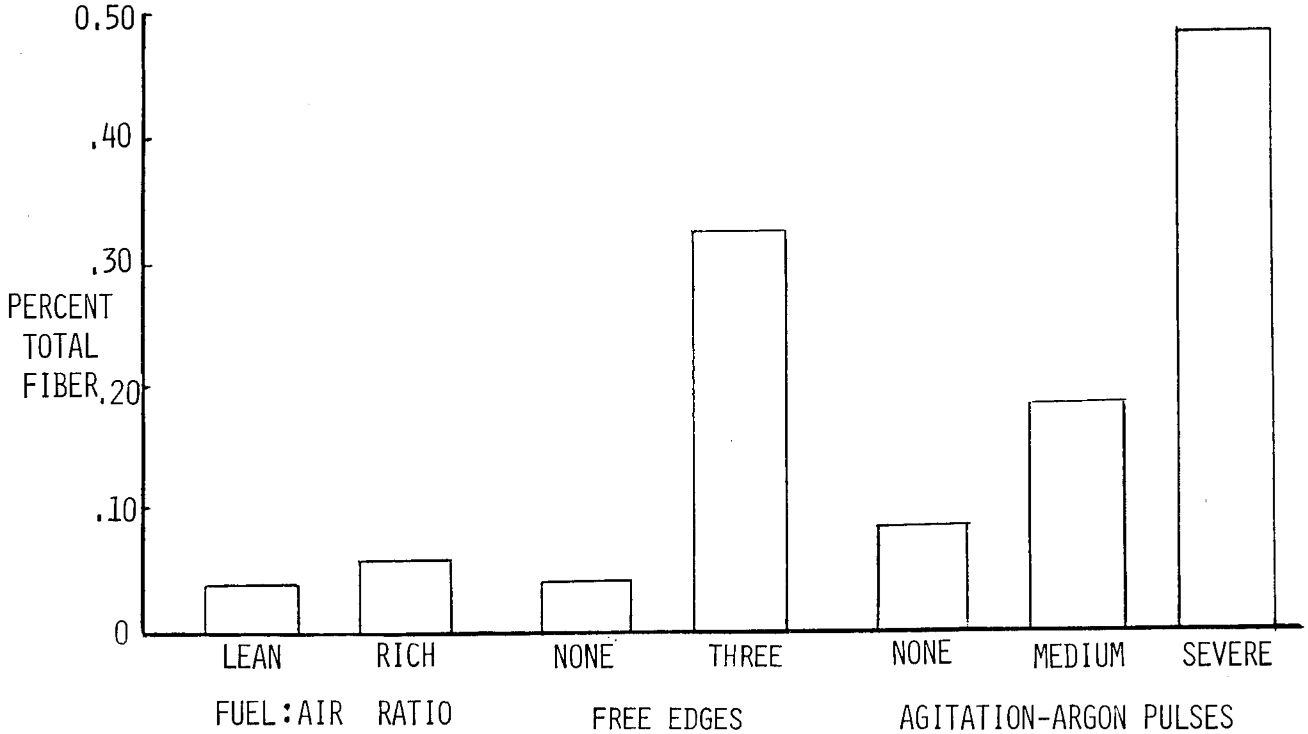


Figure 11.- Effects of fire variables on total fiber release (AVCO fire test facility).

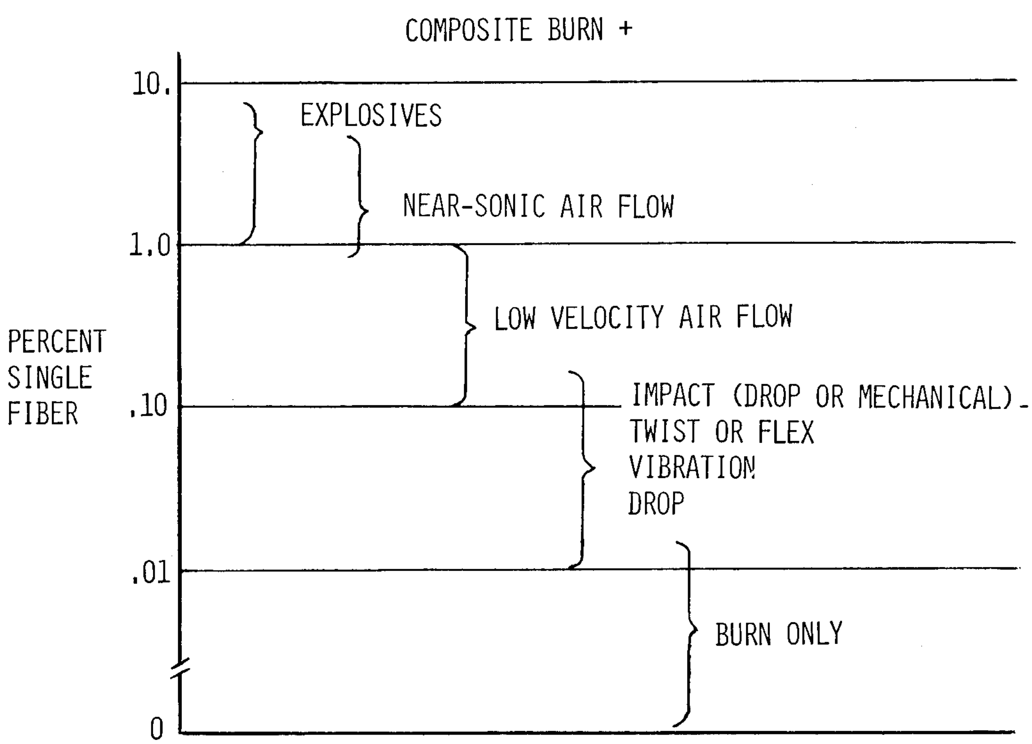


Figure 12.- Summary of effects of disturbance on fiber release from burned composites.

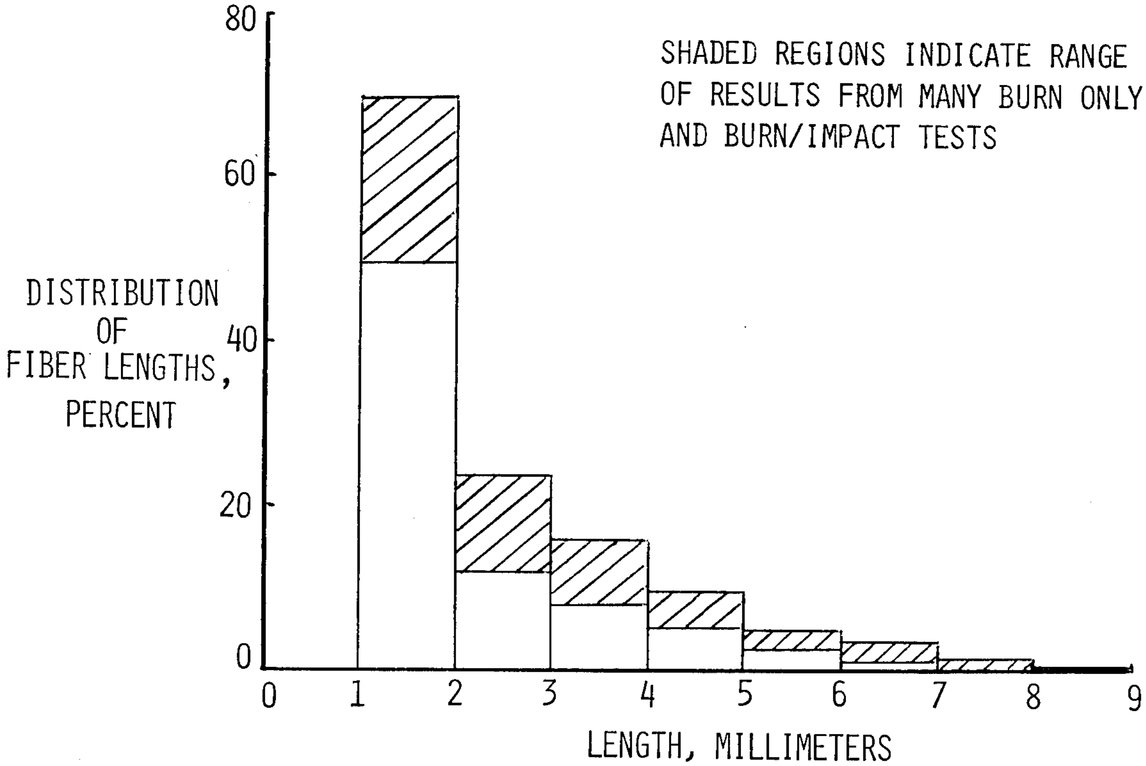


Figure 13.- Spectrum of single fibers over one millimeter long.

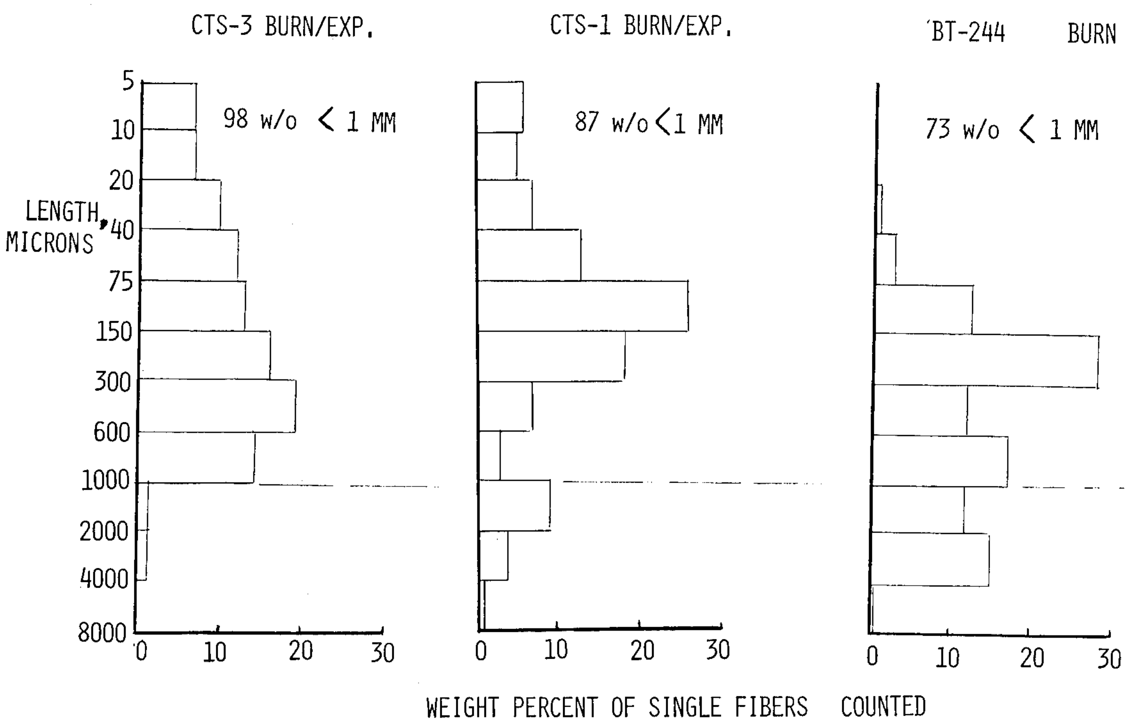


Figure 14.- Distribution of all lengths of single fibers.

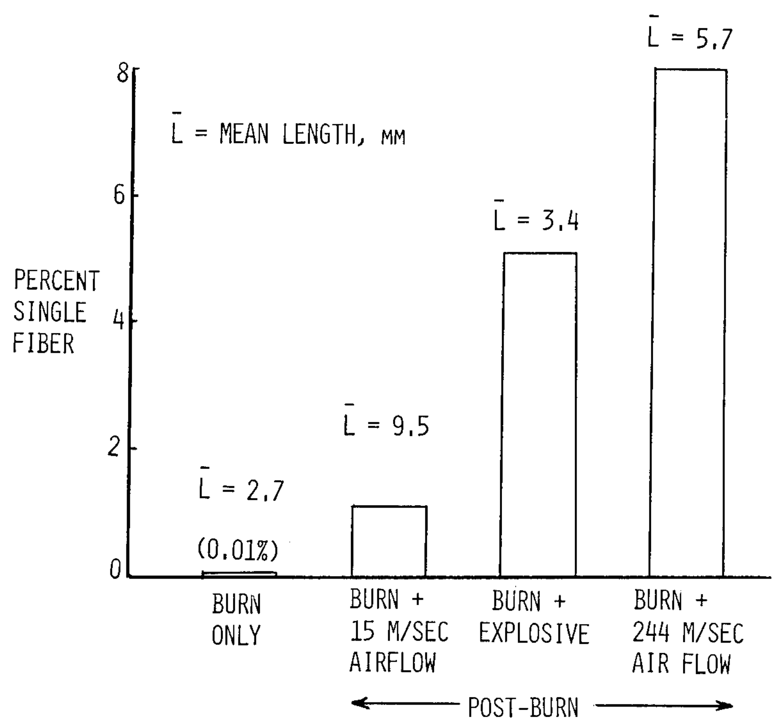


Figure 15.- Release of single fiber from hybrid glass/carbon/nomex honeycomb panel (Navy/Dahlgren chamber).

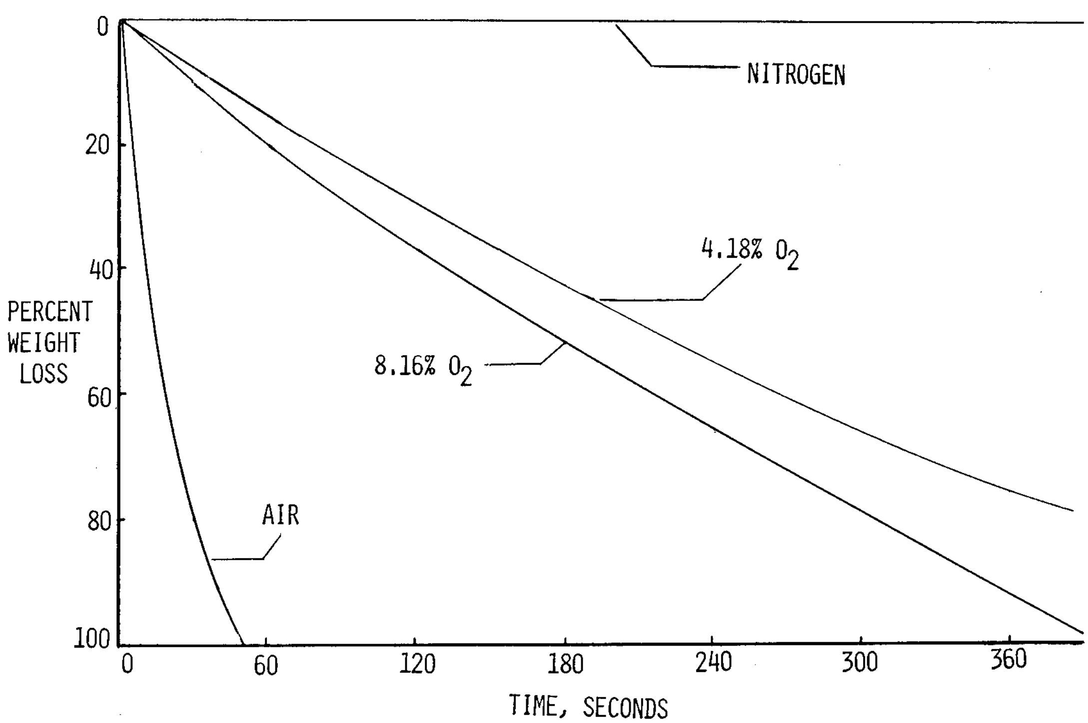


Figure 16.- Iso-thermogravimetric analyses of "AS" carbon fibers at 1250 K (1800 °F).

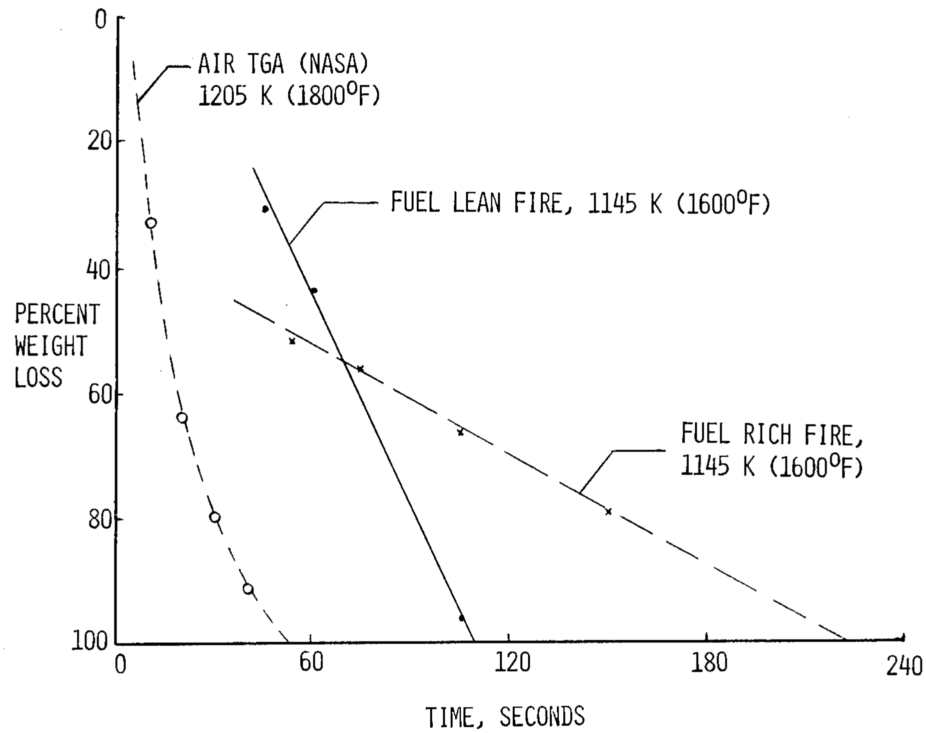


Figure 17.- Oxidative mass loss of single ply mats of carbon fibers (AVCO fire test facility).

- 50% OXIDATIVE MASS LOSS IN 240 SECOND JP-5 BURN OF SPOILER PROVED BY REDUCTION IN FIBER DIAMETER
- EQUALLY LARGE OXIDATIVE MASS LOSS SHOWN FOR OTHER THIN COMPOSITE PARTS (BARRELS, COCKPIT)
- MUCH LOWER OXIDATIVE MASS LOSSES NOTED FOR THICK COMPOSITE PANELS
- RESIDUES FROM COMBUSTION OF MATRIX RESINS MAY CATALYZE OXIDATION OF CARBON FIBERS (NOT CONFIRMED BY NASA STUDIES)

Figure 18.- Carbon fiber oxidation studies.

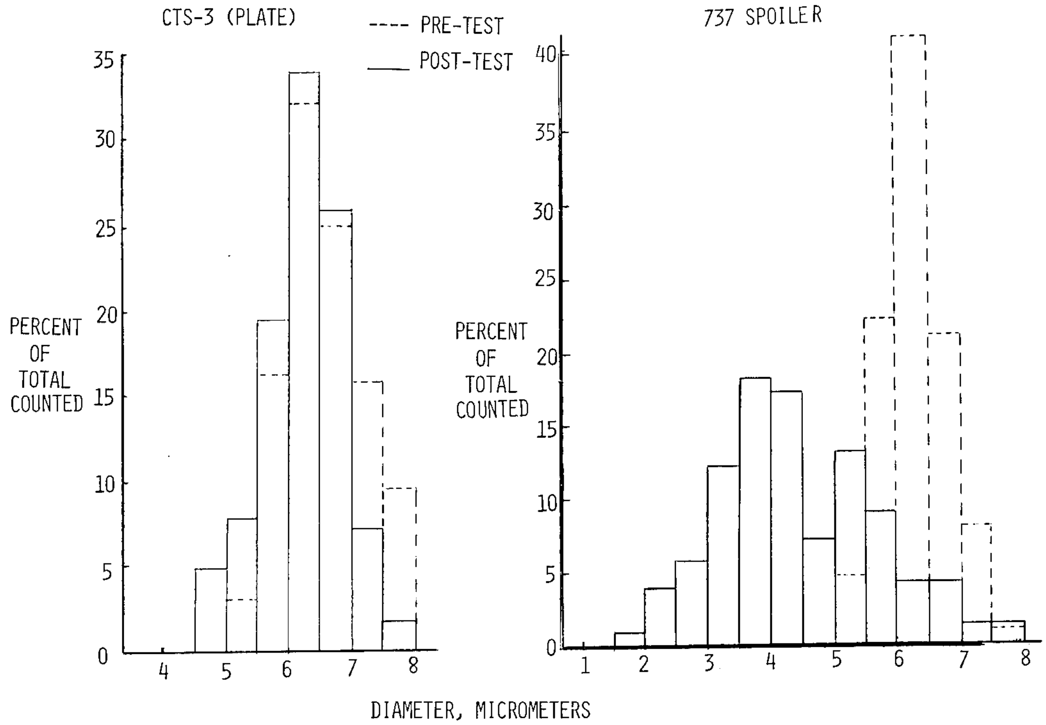


Figure 19.- Comparison of pre- and post-test diameters.

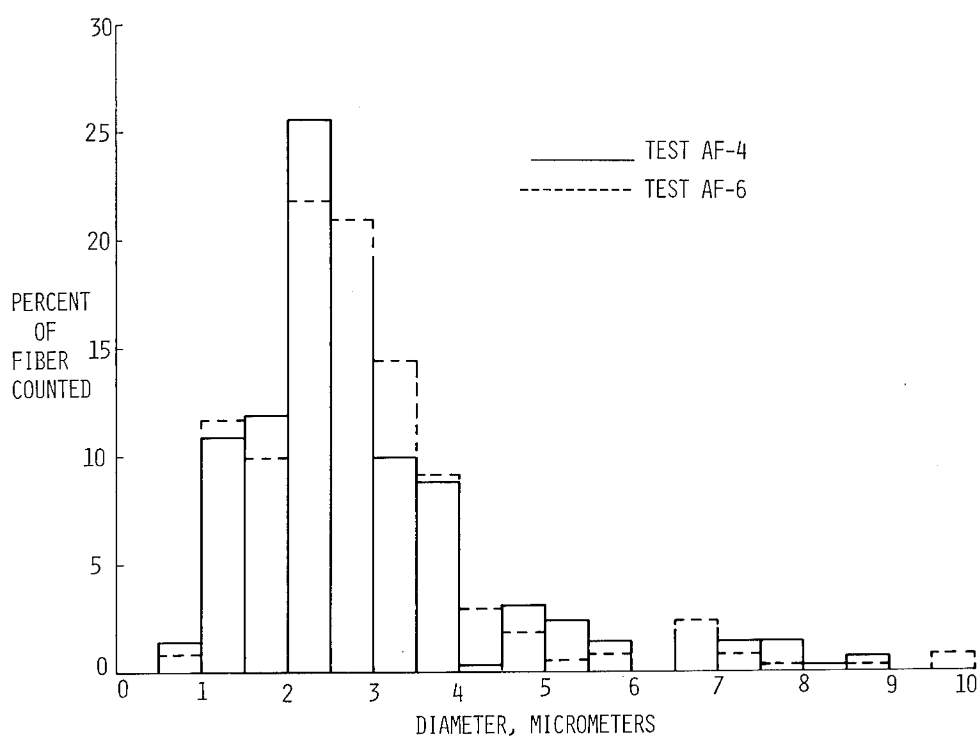


Figure 20.- Reduced fiber diameters from burn plus airflow tests.

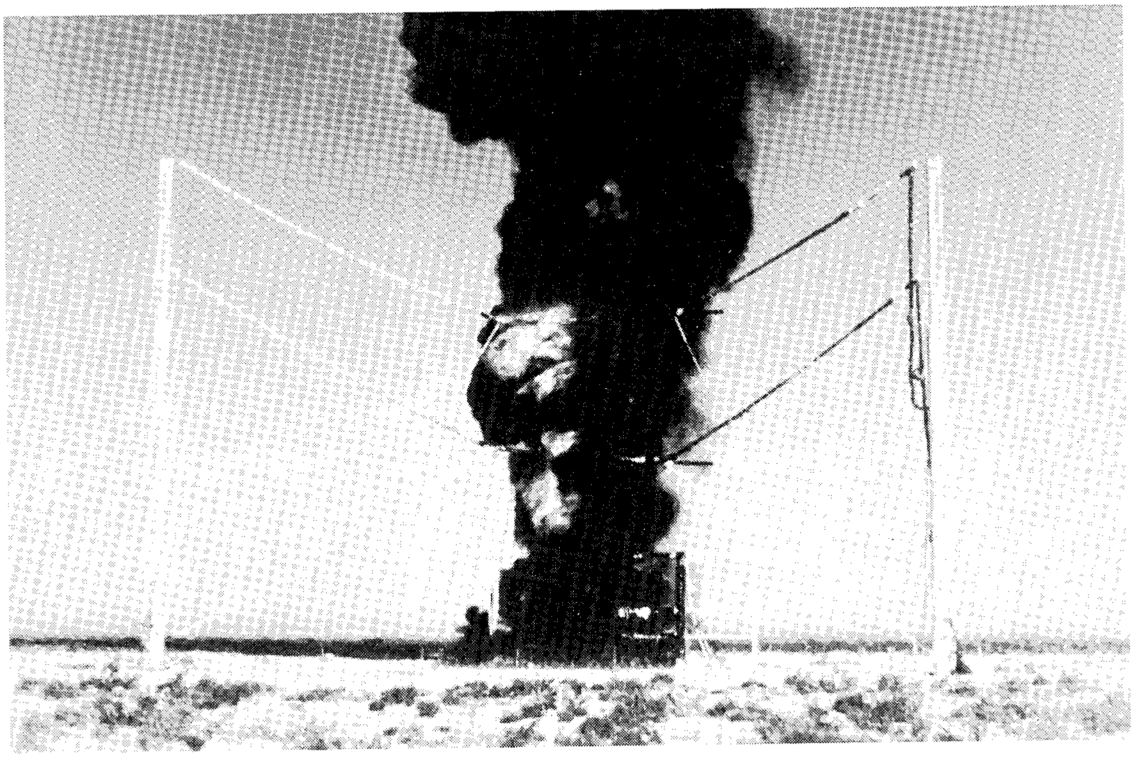


Figure 21.- Fire plume model verification tests (White Sands, New Mexico).

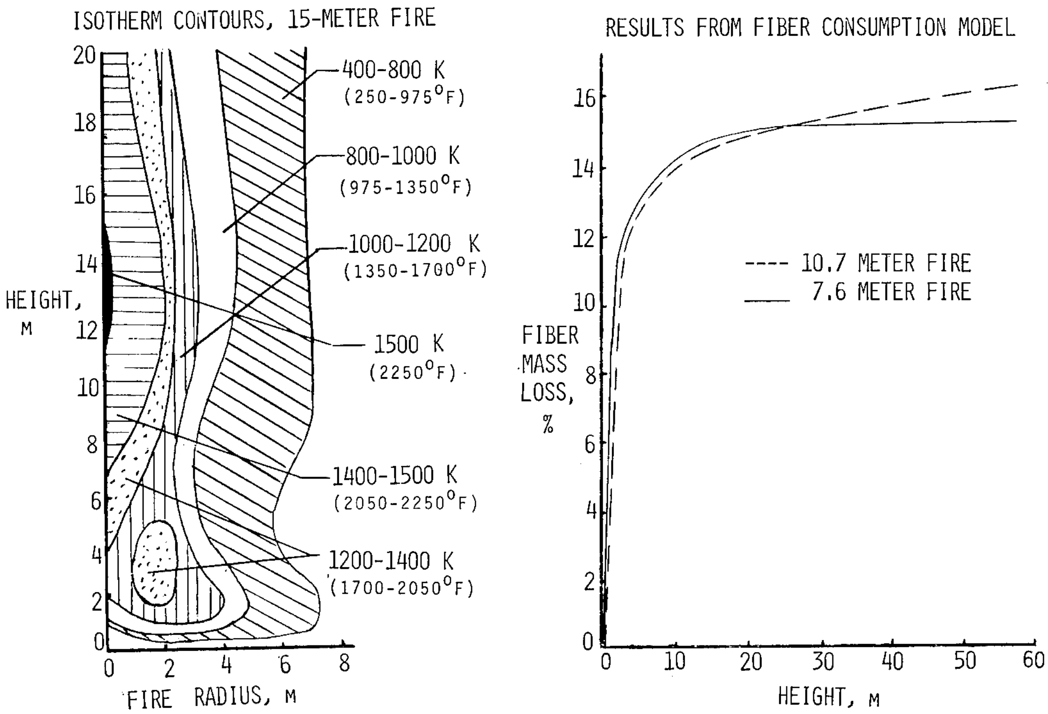
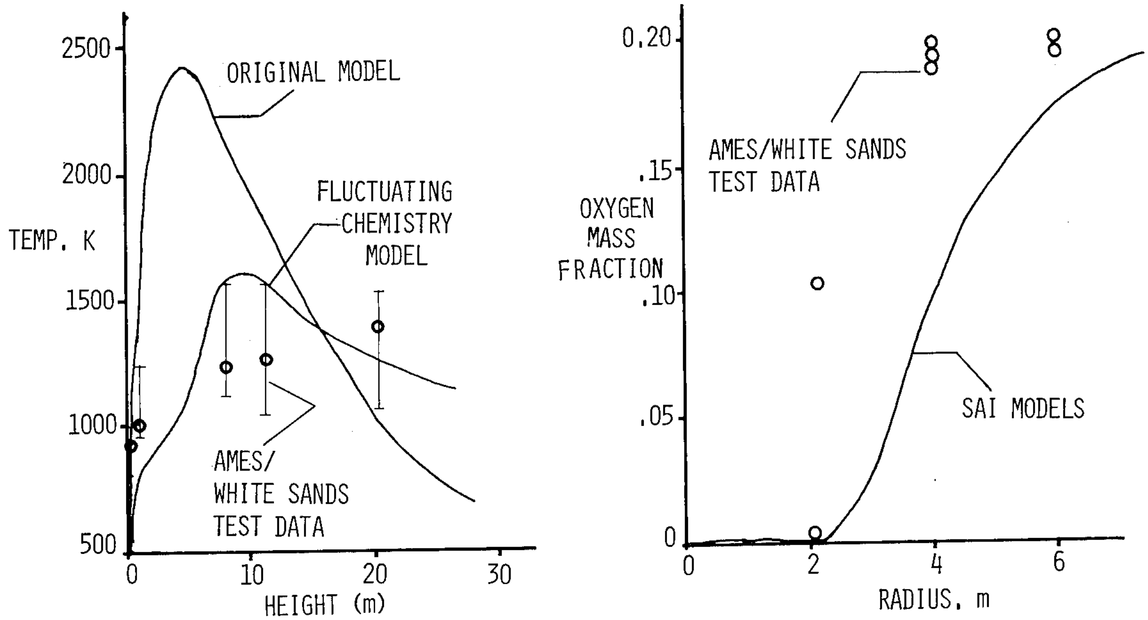


Figure 22.- Results from fire experiments and modeling.



CENTERLINE TEMPERATURE PROFILE ABOVE 15 m DIA. FIRE POOL

RADIAL OXYGEN DISTRIBUTION AT H = 6 m ABOVE 15 m DIAMETER FIRE POOL

Figure 23.- Results from fire experiments and modeling.

<u>ASBESTOS FIBERS ARE CONSIDERED HAZARDOUS IF</u>: (OSHA - 1976)

- DIAMETERS $< 3.5\ \mu m$; LENGTHS $> 5.0\ \mu m$
- ASPECT RATIO: $3{:}1 < L/D < 10{:}1$
- 8-HR T. W. A. CONCENTRATIONS $> 2 \times 10^6$ FIBERS/M^3 ($E = 5.6 \times 10^{10}\ \frac{\text{FIBER-SEC}}{M^3}$)
- CONCENTRATION, ANYTIME IS $> 10^7$ FIBERS/M^3

Figure 24.- Health hazards of asbestos fibers.

FIBER DIAMETERS, MICROMETERS	< 10	10–18	18–32	32–56	56–100	100–178	178–316	316–562	562–1000	1000–1780	1780–3160	3160–5620	5620 >
>8			0	0	0	1	2	0	1				
7–8			1	2	3	0	8	1	4	1			
6–7			0	0	11	11	21	6	2	0			
5–6			0	11	9	17	11	3	12	2	1	1	
4–5			8	22	19	29	39	21	7	5	3	2	1
3–4		0	1	8	22	41	38	36	9	8	3	1	
2–3		3	0	14	8	12	28	8	2	3			
1–2		0	2	8	13	2	6	1	2				
<1		0	0	1	2	4	1	4	0				
TOTALS				37									576

FIBER LENGTH, MICROMETERS

Figure 25.- Distribution of fiber lengths and diameters from JP-1 fuel fire.

KNOWLEDGE OF CARBON FIBER HEALTH EFFECTS:

- SMALL AMOUNTS OF FIRE-GENERATED CF HAVE DIMENSIONS COMPARABLE TO HAZARDOUS ASBESTOS

- A SINGLE STUDY OF ANIMALS SHOWED NO SHORT-TERM RISK AFTER MASSIVE DOSES OF CARBON FIBER

    - C = 3 x 10^6 FIBERS/M^3; E = 1 x 10^{12} $\frac{\text{FIBER-SEC}}{M^3}$

    - FEW CARBON FIBERS IN LUNGS: ONLY ONE WAS INTRACELLULAR

- LONG TERM RESULTS UNKNOWN

Figure 26.- Present knowledge of carbon fiber health risk.

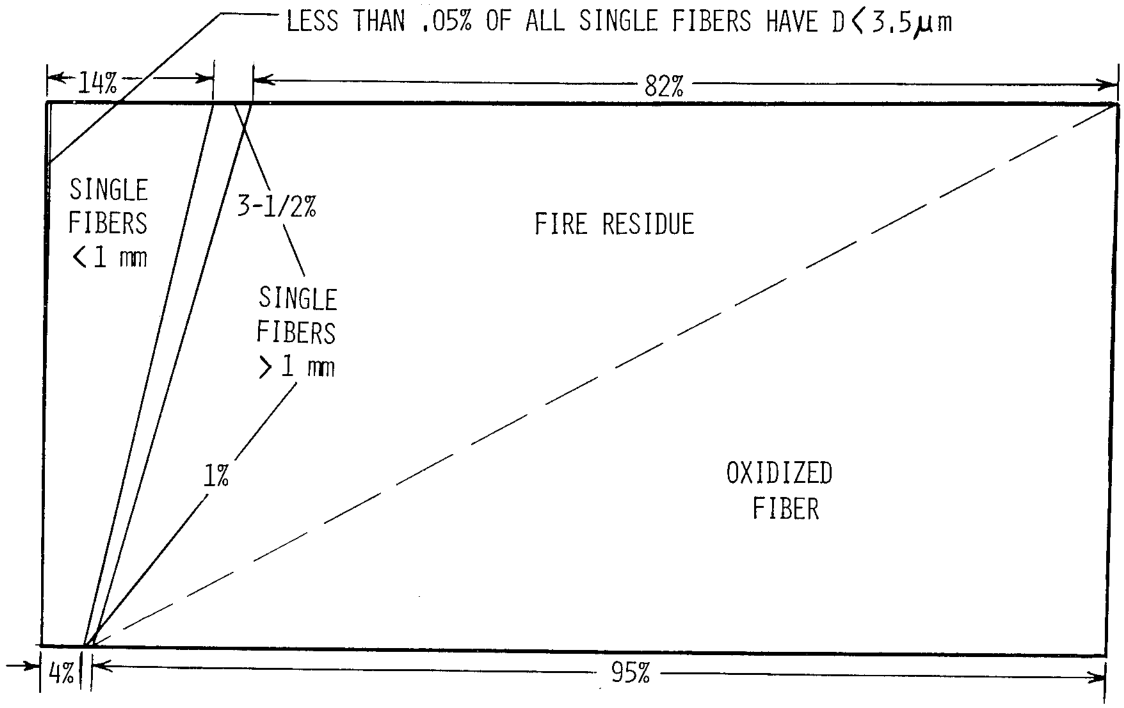


Figure 27.- Mass balance for carbon fibers from burned composites (percent of initial fiber mass).

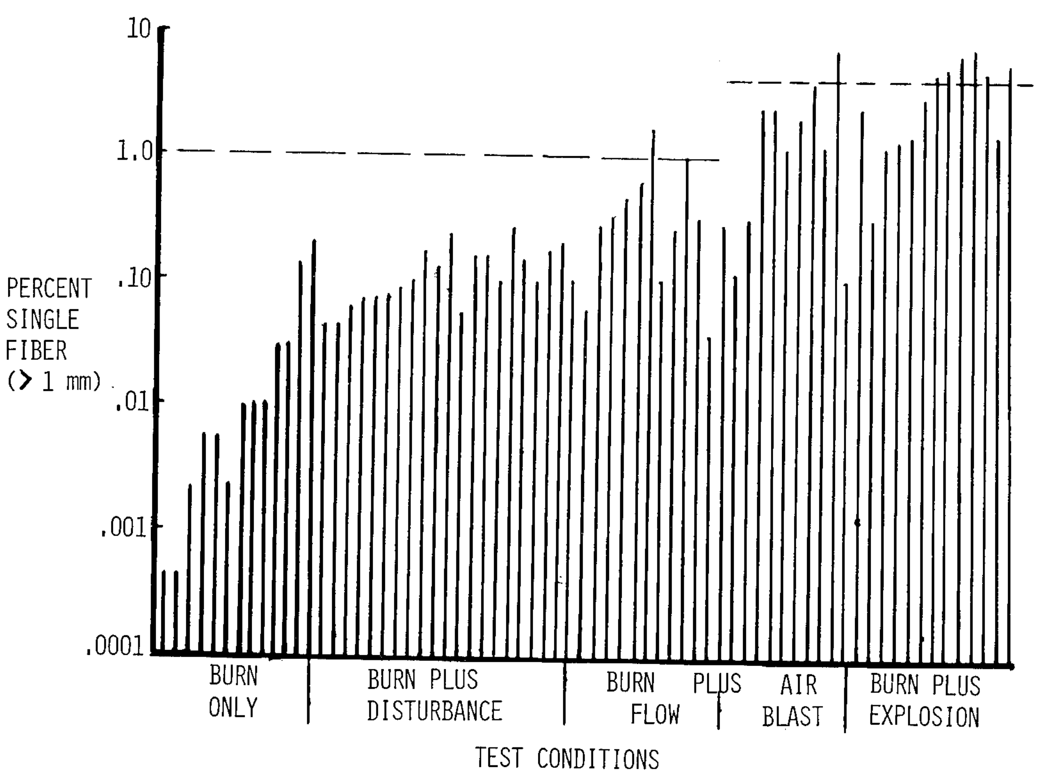


Figure 28.- Summary of all fiber release tests.

- COMMERCIAL AIRCRAFT ACCIDENT RECORDS INDICATE:
  - 85% OF ACCIDENTS WITH FIRES HAVE NO EXPLOSIONS
  - 15% OF ACCIDENTS WITH FIRES DO HAVE EXPLOSIONS
- OF TOTAL AMOUNT OF CF IN COMPOSITE PARTS EXPOSED TO FIRE:
  - 1% WILL BE RELEASED FROM FIRES ALONE
  - 3-1/2% WILL BE RELEASED FROM FIRES AND EXPLOSIONS
- FOR EVERY KILOGRAM OF CF RELEASED:
  - 5×10^9 SINGLE FIBERS WILL BE RELEASED
  - EXPONENTIAL DISTRIBUTION OF FIBER LENGTH WITH MEAN OF 2 MILLIMETERS
  - FIBER DIAMETERS SAME AS ORIGINAL (8 μM)

Figure 29.- Recommended accidential carbon fiber release for risk analysis computations.

DISSEMINATION, RESUSPENSION, AND FILTRATION OF CARBON FIBERS

Wolf Elber
NASA Langley Research Center

INTRODUCTION

The carbon fiber study has been structured like other atmospheric pollution problems. The source produces the material, in this case carbon fibers; the atmosphere transports and distributes them; and at the end of the chain the fibers produce effects, in this case the disruption of electrical devices. Both the source and the effects elements of this study had to be generated specifically for this problem; whereas the transportation element could be mostly adapted from other pollution studies.

For the fire plume aspect of transportation, the smoke stack models were used for the determination of the height at which the plume becomes neutrally buoyant. However, the differences between an uncontained open fire plume and an industrial smoke stack are large enough to have required some model verification testing. This work was performed at the White Sands Missile Range.

Many models exist for the cloud transport phase of the problem. These models have a large empirical data base from pollution work with gases such as sulphur dioxide from industrial sources, with liquid droplets from aerial spraying, and with solid particles such as fly ash from smoke stacks. Those models are only sensitive to the still air fall velocity of the individual particles, and have been adopted into the risk assessment studies because they have proven successful in work for the Environmental Protection Agency.

Resuspension of particles was found to be a less developed much more complex science which had developed around the need to understand soil erosion in some states and long term radioactive pollution in other states. However, what appeared applicable to round soil particles did not appear to be valid for our high aspect ratio fibers. A special series of tests was therefore conducted to monitor the resuspension of fibers from a desert land patch with a known deposition of fibers. The results of those tests led to the conclusion that resuspension was a minor problem and that the risk assessment should be based on the first-time source.

Filtration of fibers and the their entry into buildings is a subject for which models existed and only specific filter tests had to be performed. The transfer function models are essentially micro-dissemination models assuming perfect mixing of the atmosphere within the buildings.

Many organizations were involved in assembling the methodology which prescribes the path for the fibers from the source to the vulnerable equipment. This presentation contains a brief outline of the methodology used and the data developed for the four main topic areas: Fire Plume, Dissemination, Resuspension, and Filtration.

MEASURES OF FIBER POLLUTION

Typically a vulnerable electric instrument may blow cooling air over the electric circuits, and blow the fibers across contact pairs. The rate at which fibers might strike a contact pair and cause a failure is therefore proportional to the concentration of fibers in the air. In this presentation the symbol C is used for concentration. Its units are fibers/unit volume of air (f/m^3). The total risk of failure of an instrument is proportional to the exposure E, which is defined as the time-integral of the fiber concentration,

$$E = \int C \, dt \qquad f\text{-}s/m^3$$

or if the concentration C is constant for a time t, the exposure is the product of time and concentration

$$E = C \times t \qquad f\text{-}s/m^3$$

For most instruments the risk of failure is only a function of the exposure E, and it has therefore become the main measure of carbon fiber pollution.

Most detectors of fibers deposit the fibers on a surface, and the deposition density D is the number of fibers per unit area (f/m^2).

The deposition density is related to the exposure through the deposition velocity

$$D = E \times \mathbf{v} \qquad f/m^2$$

where v is the flow velocity of the air for filter type collectors or the fibers' free fall velocity $\mathbf{v_s}$ for flat surfaces.

METEOROLOGY FOR DISSEMINATION

The strength of the sun's heating of the ground has the greatest influence on the turbulence of the atmosphere and on the dispersion of particles.

The sketches in Figure 1 show a smoke stack in three weather conditions. In sunny weather with low winds the radiation from the sun first heats the ground. Some of the heat is conducted to the lower few meters of the air. This stack is unstable, and the heat is distributed vertically by convection, until the atmosphere is layered at the dry adiabatic lapse rate to the height of the inversion. Typically during the heating portion of the day the temperature distribution changes from State I to State II. The convection patterns are responsible for very rapid mixing of the smoke plume in the atmosphere.

At the other end of the scale, with no solar heating the earth radiates out heat and cools. When the atmosphere is stably layered, the bottom layers will loose heat to the ground by conduction forming a stronger inversion. This atmosphere sustains no turbulence and smoke plumes mix extremely slowly. These conditions lead to the highest pollutant exposures downwind.

Between the two extremes there is the neutrally buoyant atmosphere with little or no heat flux. These conditions usually occur after the passage of fronts in strong winds under overcast skies. The turbulent mixing under such conditions is due to the turbulence accompanying the wind. The mixing is faster than in stable weather, but slower than in unstable weather.

For dissemination analysis stability indices have been developed. The Pasquill-Gifford stability classes for the three main weather conditions are shown in Figure 1. Cloud spread angles have been empirically determined for each of these classes.

PLUME MODELLING

Figure 2 shows a schematic view of a smoke cloud rising from the site of a large pool fire. When the gases are hot and buoyant the fire plume is extremely turbulant and mixes rapidly with ambient air until it reaches neutral buoyancy. The thermal buoyancy in that phase dominates the spread and rise of the clouds, and special fire plume models have been developed to predict the height and the spread of the fire plume to the point at which it becomes neutrally buoyant, that is the "stabilization point".

Beyond the stabilization point the meteorology determines the spread of the drifting smoke cloud. The Gaussian dissemination models have been developed to predict the exposure patterns downwind. The fire plume models and the dissemination models are matched together at the stabilization point.

FIRE PLUME MODELS

The fire plume models are based on material contained in a paper by G. A. Briggs (1970) presented at the Second International Clean Air Congress.

Although the model was developed for smoke plumes from industrial exhaust stacks, it provides good estimates of the stabilization parameters for the concentrated liquid-fuel pool fires of interest here.

The model is sensitive to the stability of the atmosphere and the logic changes between stable and unstable atmospheres.

In stable temperatures for instance the stabilization height is given as

$$H = 2.9\sqrt[3]{F/u.s}$$

Where F is the total heat flux, u is the wind velocity and s is the potential temperature gradient.

The size of the cloud is determined by the entrainment of air and in most cases the diameter grows linearly with height so that

$$D = 0.6\,H$$

DISSEMINATION MODELLING

The most appropriate dissemination models for a risk assessment are the Gaussian Dissemination Models.

In these models the material is given the Gaussian bell-shaped distribution shown in Figure 3. As the cloud drifts downwind it grows in diameter depending on the instability of the atmosphere. The growth angles have been determined empirically from many observations of smoke plumes.

As the cloud grows and drifts downwind it will begin to intercept both the ground and the inversion as shown in Figure 4. Inasmuch as the growth is dependent on the turbulence in the layer between the ground and the inversion, the models are refined not to allow the cloud to grow through the inversion, but to reflect back the pollutant into the layer between ground and inversion. At the same time particles will deposit on the ground at a rate dependent on particle concentration and their fall velocity. Empirical data show that reflection of 70% of the particles from the ground provides exposure patterns consistent with the fall velocity of the particles.

Figure 5 shows two typical exposure patterns. The lines of constant exposure are termed "isopleths". In the stable atmosphere the spread of the cloud is narrow, but high exposure levels may persist for up to 100 km. In the unstable atmosphere the spread of the cloud is wide, but does not persist for the same distances.

The deposition rate anywhere in the affected area is dependant on the concentration and the fall velocity

$$\dot{D} = C \times v_s$$

The total deposition at one point is

$$D = v_s \int C \, dt = v_s \times E$$

and the total deposition over the entire area is

$$\int D \, dA = v_s \int E \, dA$$

or

$$N = v_s \int E \, dA$$

where N is the total number of particles in the pollutant cloud. This equation indicates that the fire and meteorological conditions only affect the distribution of the exposures, the total area coverage however is determined by the amount of material in the source.

If the material could be uniformly distributed at exposure levels E over an area A , then we have the simple relation

$$N = v_s E A$$

Figure 6 is a parametric plot of the area covered to an exposure E as a function of the mass of single fibers in the source. As an example, the worst case analyzed in the risk assessment represented a source of 375 kg of single fibers. The plot shows that this amount of fibers could cover a whole city to an exposure of 5 X 10^5, or five city blocks to an exposure of 10^8. The damage potential from such a release will be discussed in the next presentation.

RESUSPENSION OF CARBON FIBERS

Carbon fibers deposited on a surface may be resuspended by a disturbance such as wind or traffic. This phenomenon was investigated to determine if resuspension could represent a significant contribution to the carbon fiber risk.

Figure 7 shows the logic diagram for the type of surface on which fibers are first deposited. Fibers deposited on water will sink and cannot be resuspended. Fibers deposited in vegetated surfaces will fall so deep that the winds required to resuspend the particles cannot reach the particles. But fibers deposited on flat hard surfaces could be resuspended. One test series was conducted to monitor the resuspension of fibers from a desert surface. From an original source of 23 kg scattered over an area of 60 X 80 m The daily downwind fiber flux is plotted in Figure 8. The data was collected for three years. The vertical and horizontal distributions were not defined, but on the assumption that the flux was uniform over a downwind area of 1000 m^2, we can calculate a total flux of 0.1 kg of 4 mm fibers or less than 0.4% of the available total source. At the same time the average length of the captured fibers changed from an initial mean length of 7 mm to a final mean length of 1 mm, while the source material left on the ground clearly retains the initial lengths of 7 mm. The fragmentation indicates that the fibers released are broken from the clumps of source fibers, most probably by the saltation of sand particles.

Because the fraction of fibers resuspended is small, because only special areas are suitable for resuspension, and because fibers appear to be fragmented in the process of resuspension, the phenomenon of resuspension was not considered further in the risk assessment.

TRANSFER FUNCTIONS

The transfer function of a building or instrument enclosure is the ratio of internal fiber exposure to external fiber exposure.

Filtration, airflow, and settlement velocity are the parameters controlling the transfer function.

Filter tests have been carried out at the Ballistics Research Laboratories to define the filter transmission factors as a function of fiber length for many

common filter media. Figure 9 shows the results of such tests on a typical window-screen and a furnace filter. Both filters are more effective against long fibers than against short fibers. As a result the mean fiber length as well as the number of fibers are reduced by the filter.

Figure 9 shows an initial exponential fiber length distribution, and the distribution after filtration. The mean fiber length has changed from $l^* = 2$ mm to $l^* = 0.9$ mm, and the transfer function for fibers longer than 1 mm is 0.13.

Such analytical refinements have not been introduced into the risk assessment. Instead, the contractors have used the filter factors appropriate for the 2 mm mean spectrum length and have assumed that the transmitted spectrum remains exponential.

The Bionetics Corporation has tested filtration equipment from commercial aircraft. Both water separaters and air cleaners have very low transmission factors, but also cause severe fiber fragmentation. In a separate test the fragmentation of fibers was evaluated by passing 3 mm fibers through a curved duct. Figure 10 shows a schematic of the test apparatus together with the test results. At low flow speeds most fibers travel through the curved tube intact, but at fiber speeds of 11 m/s and higher virtually all fibers were fragmented into lengths less than 1 mm.

Aircraft ventilation air drawn from the compressor stages of the turbines typically would undergo many turns and much higher speeds. We have therefore assumed that fibers longer than 1 mm would be fragmented into lengths smaller than 1 mm in aircraft engines.

Models for the analysis of transfer functions have been available from previous studies. The transfer function for an enclosure can be shown to be the ratio of fiber inflow rate to the fiber loss rate.

The inflow rate is given by the airflow rate times filter transmission factor. The fiber loss rate is made up of outflow losses, losses in the recirculation filter, and losses due to fiber deposition.

Figure 11 shows the transfer function calculations for a 200 m^2 residence with open windows protected by wire screens. The calculations show that even with open windows transfer functions as low as 0.01 are to be expected.

CONCLUSIONS

The elements of the fiber transport chain have been studied. The mathematical models had been established for other pollution problems and were found to be appropriate for the carbon fiber problem.

A particular study was made to establish the possibility of resuspension. The data showed that resuspension cannot be a major contributing factor to the risk.

Filtration and fragmentation tests were run to provide the necessary data base for transfer function calculations. The data showed that filters are much

more effective than assumed in the preliminary study and that in high velocity air handling systems significant fiber fragmentation will change the fiber spectrum to shorter mean lengths.

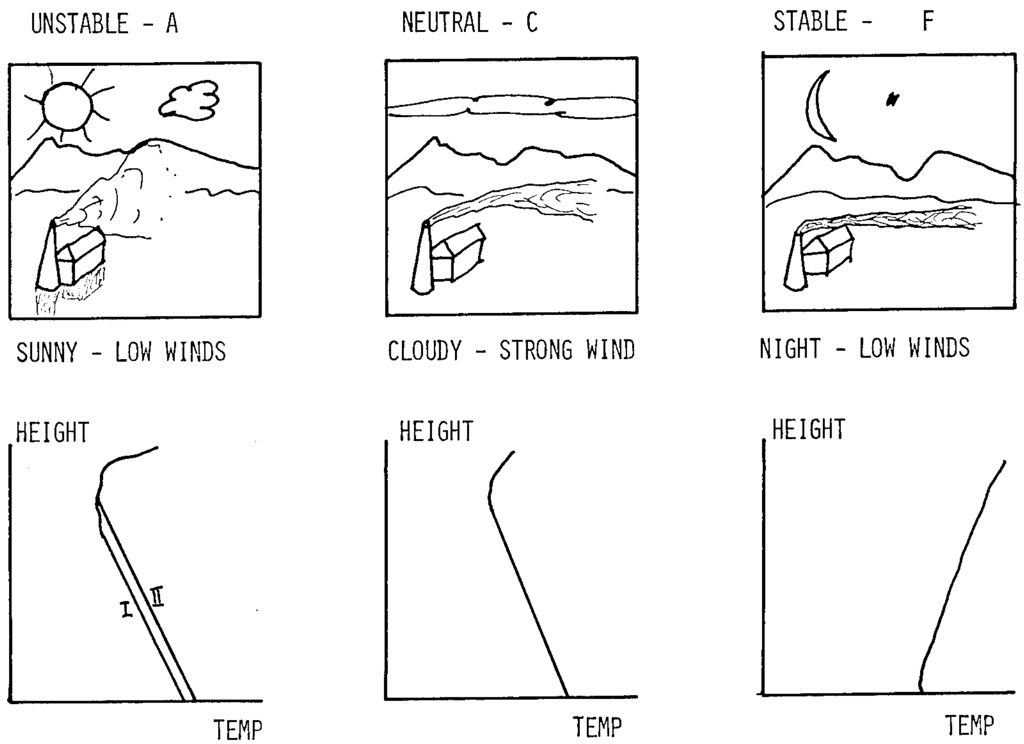


Figure 1.- Dissemination meteorology with Pasquill-Gifford stability classes A, C, and F.

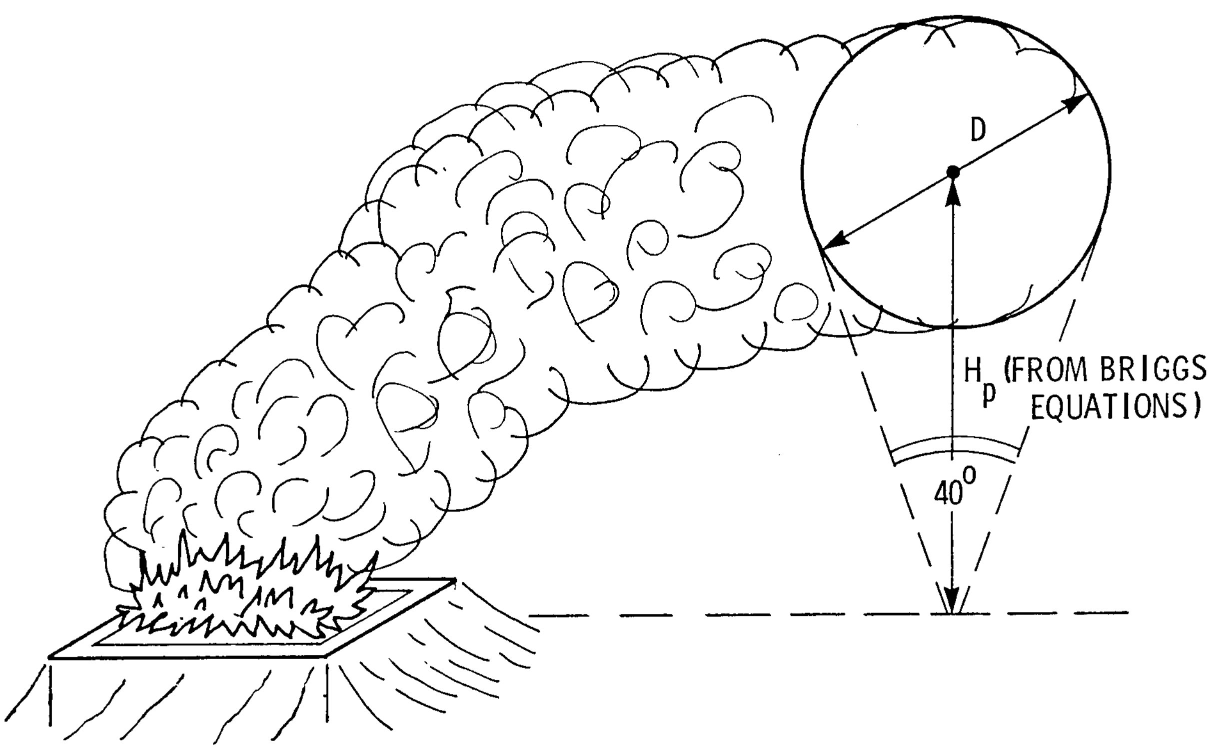


Figure 2.- Characteristic smoke plume development.

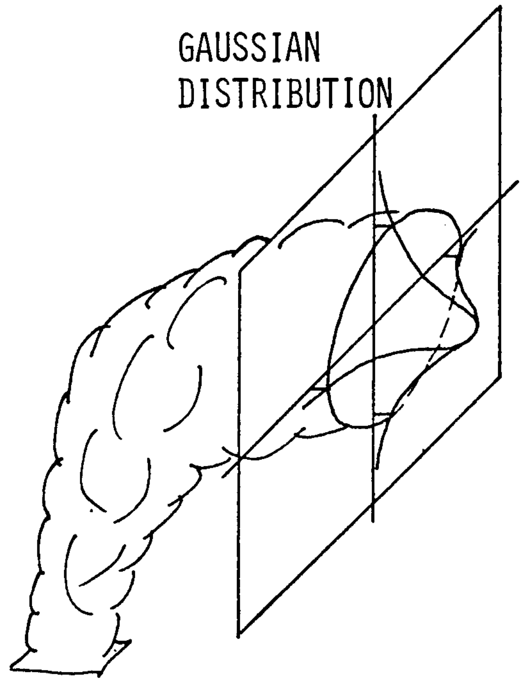


Figure 3.- Gaussian distribution of pollutant
in a drifting cloud.

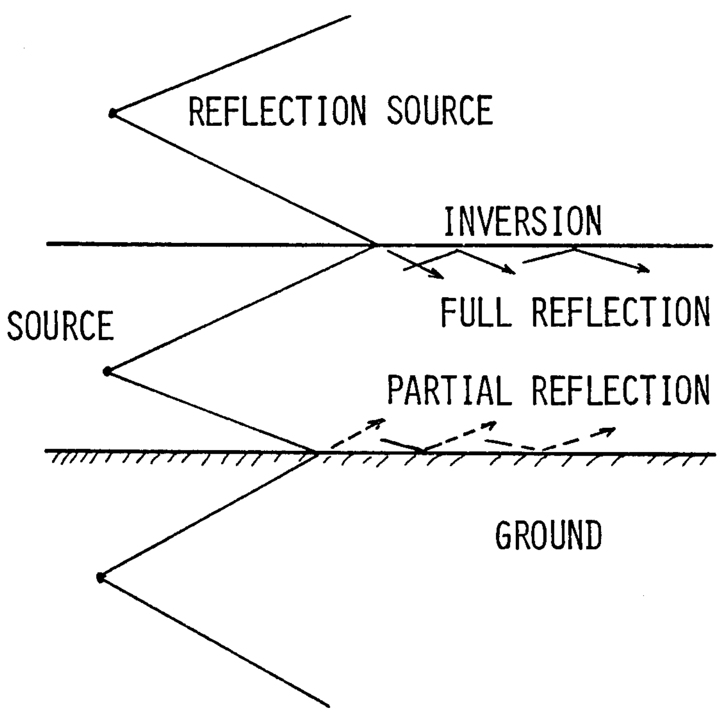
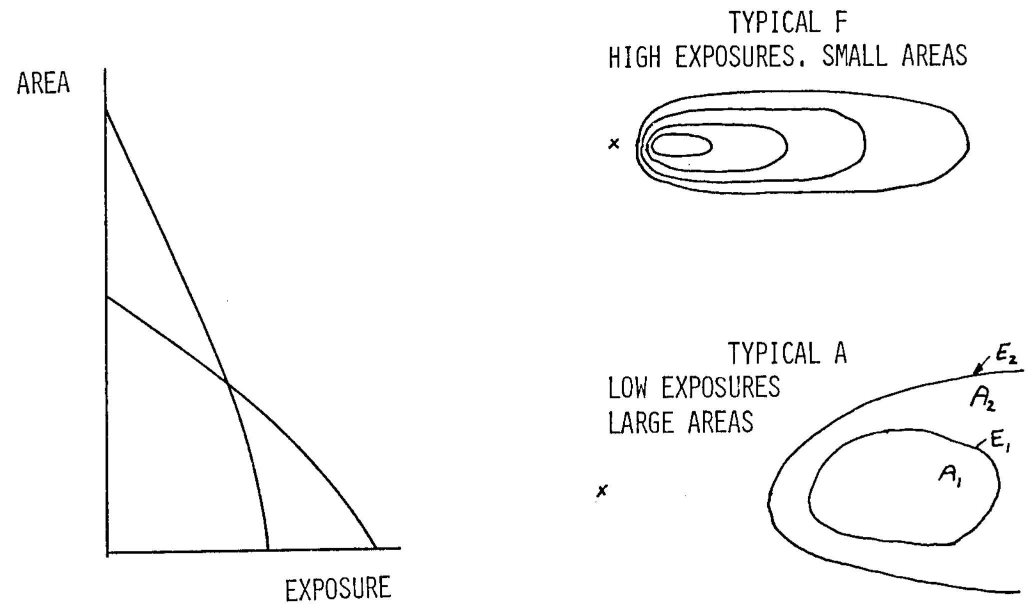


Figure 4.- Pollutant cloud growth with reflection from
inversion and ground.



TOTAL DEPOSITION EQUATION: $\sum E_i A_i = N / v_s$

Figure 5.- Typical exposure patterns and area coverage definition.

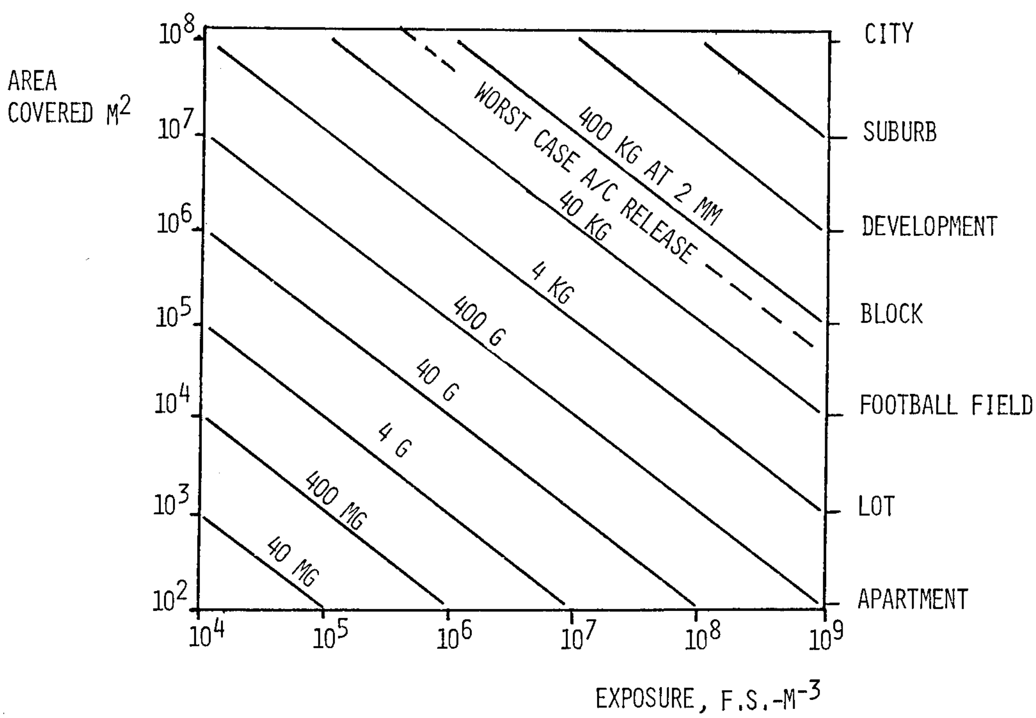
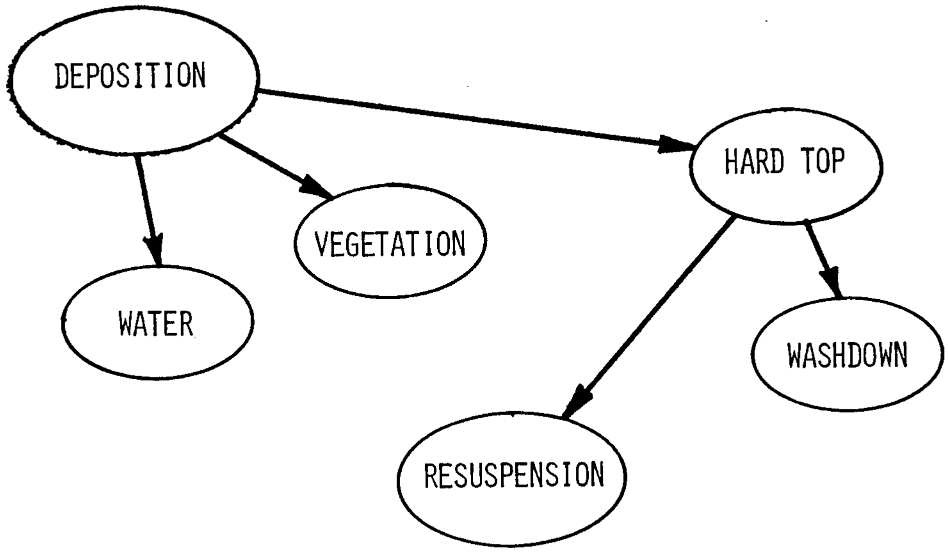


Figure 6.- Parametric plot of carbon fiber area coverage limit.



• RESUSPENSION POSSIBLE FROM FEW AREAS.

Figure 7.- Resuspension logic chart.

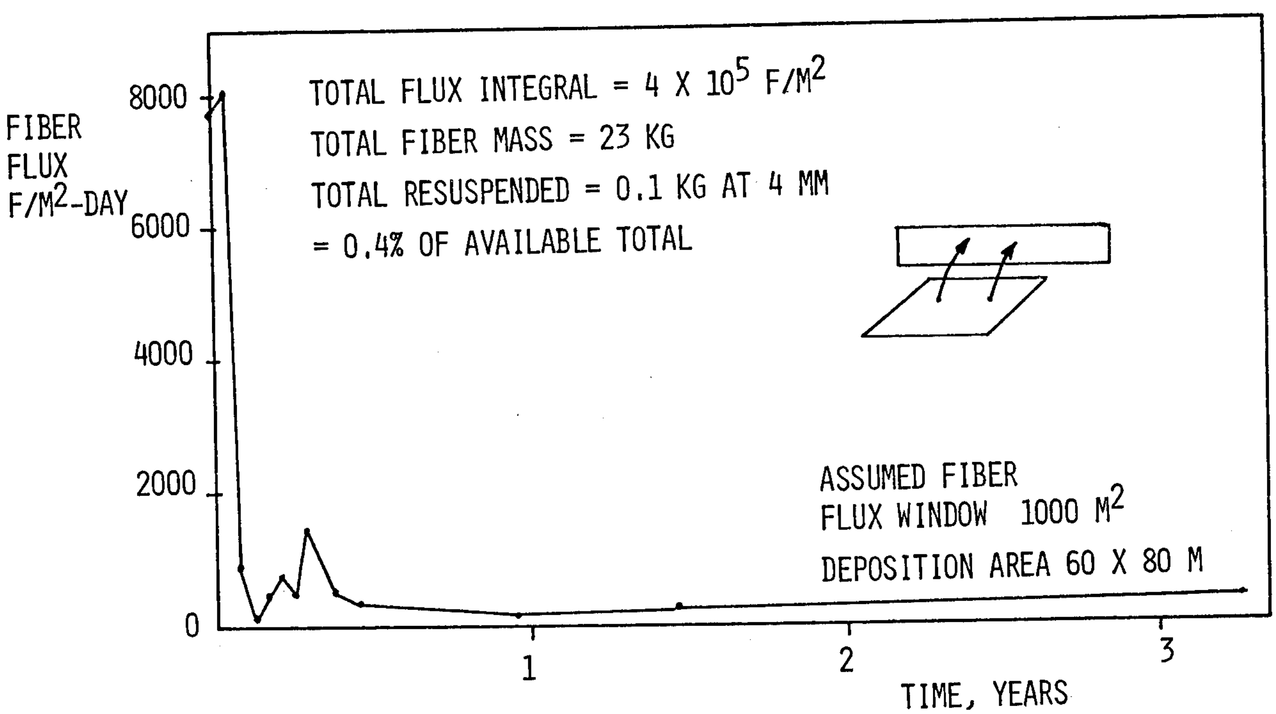


Figure 8.- Resuspension data.

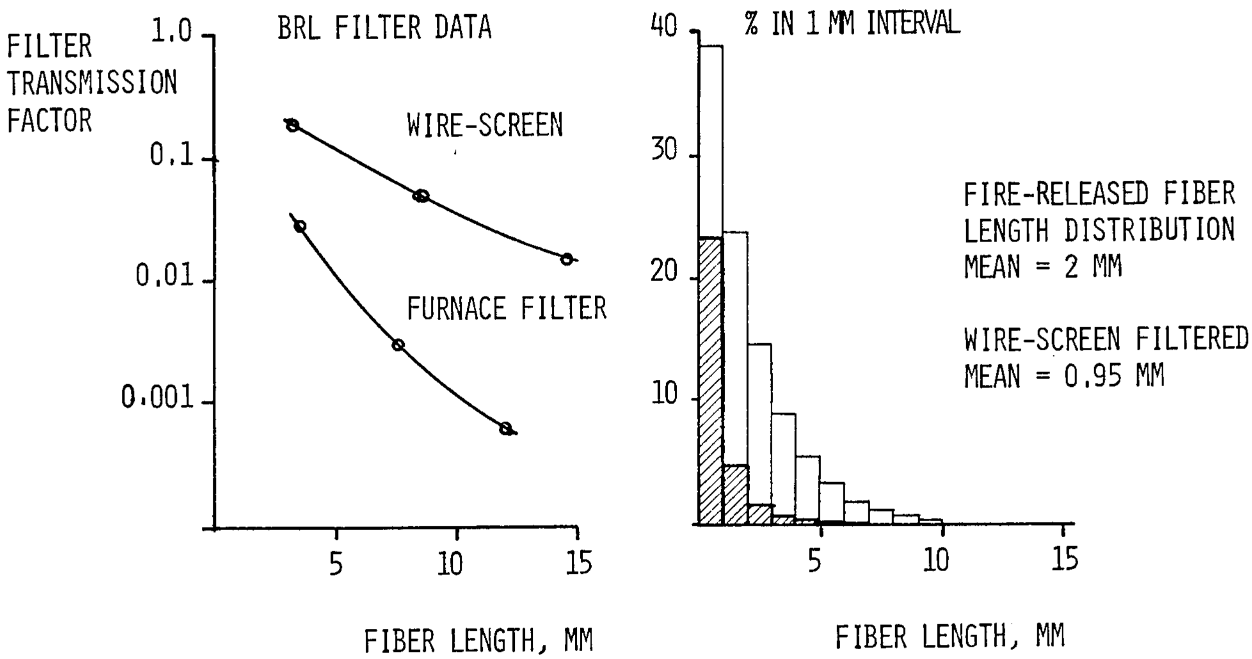


Figure 9.- Filter data.

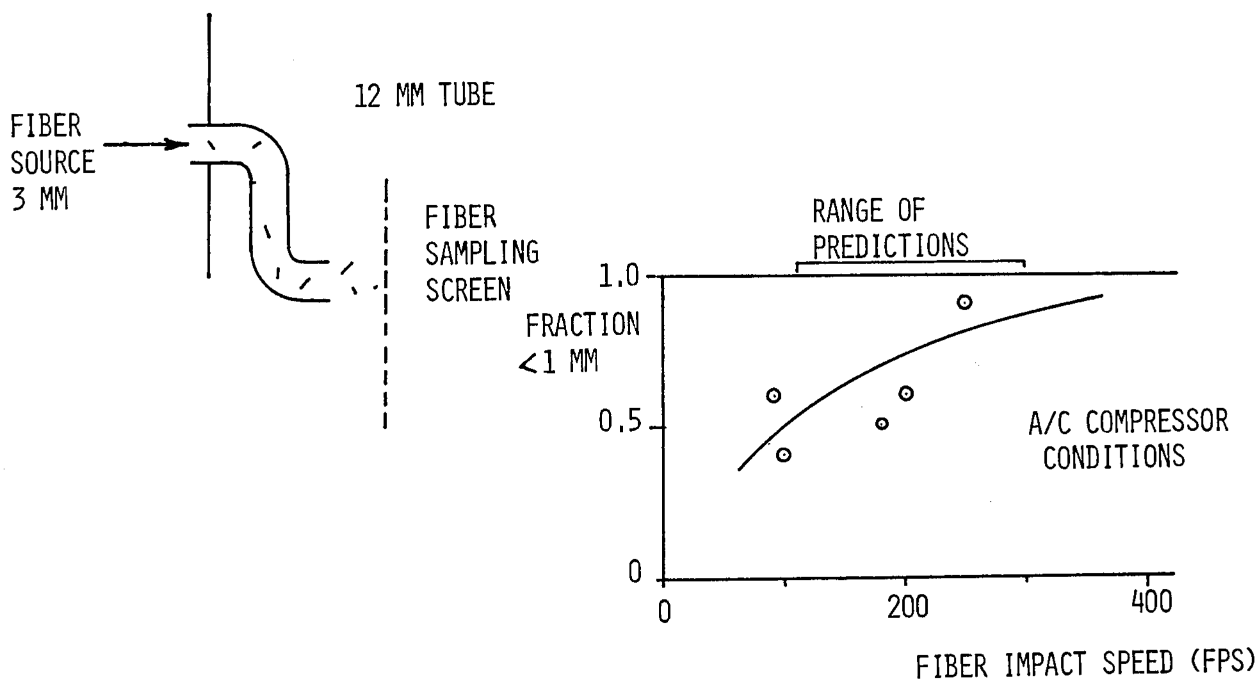
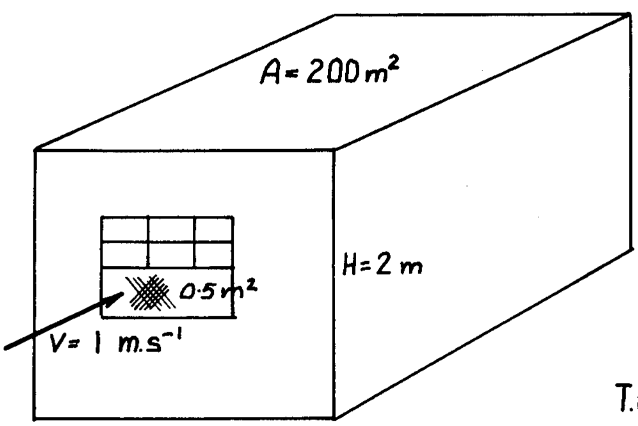


Figure 10.- Fragmentation data.



$$T.F. = \frac{\text{FILTER FACTOR} \times \frac{Q_i}{V}}{\left(\frac{Q_i}{V} + \frac{Q_R(1-\mu_F)}{V} + \frac{V_s}{H}\right)}$$

$$T.F. = \frac{0.2 \times 1.2 \times 10^{-3}}{(1.2 \times 10^{-3} + 7.5 \times 10^{-4} + 1.25 \times 10^{-2})}$$

$$= 0.01$$

$0.5\ m^3 s^{-1} = 1000\ cfm$

$\equiv$ ONE WINDOW FAN

Figure 11.- Transfer of carbon fibers into buildings.

EVALUATION OF EQUIPMENT VULNERABILITY

AND POTENTIAL SHOCK HAZARDS

Israel Taback
The Bionetics Corporation

Since the last report on this subject made on October 31, 1978, additional data has been collected on equipment which may be affected by graphite fibers released from aircraft accidents and on evaluating the significance of the shock hazard on consumer equipment. As outlined in Figure 1, this paper will describe the vulnerability tests, provide some illustrations of specific test results and discuss the parameters which affect vulnerability. The shock hazard for a hypothetical set of accidents will also be computed and evaluated. Figure 2 lists some of the conditions which bounded the parameters of the tests made in the Langley Research Center and Aberdeen Proving Ground test chambers. In general the tests were conducted with moderate graphitization fibers such as T-300, lengths were between 1 and 10 millimeters and with the equipment under test operating. Exposures were limited to values of 10^8 fiber seconds per meter^3, both for practical reasons of test duration, and because at this level very small national damage costs would be encountered. Limited tests were done with equipment either nonoperating or with simulated environments subsequent to fiber exposure, except for avionics equipment, in which expected flight environments were simulated.

Figures 3 and 4 list the results secured. Many pieces of equipment did not fail within the test limits under exposure to graphite fibers or when tested with a fiber simulator probe. The latter technique was used in devices wherein the number of electrical nodes were limited and could be easily sampled manually.

Some of the parameters which affect vulnerability are shown in the following figures. Figure 5 shows the effect of fiber length on two pieces of equipment. The power amplifier shows a consistent trend with length. In the range of average fire-emitted fiber lengths (2 to 4 mm) the exposure required for failure are

$$\overline{E} = 4 \times 10^6 \ (1/\ell)$$

This inverse trend with length is typical of equipment not protected with a case and/or filter. The ATC transponder has a nontypical response which is caused by the type of openings in the case. These are holes, approximately 3 mm in diameter. The transfer function for fibers through these openings varies inversely with fiber length for lengths equal to or larger than the holes so that there is a relative invulnerability to fibers longer than 3 mm. This size of opening is common in many types of avionics equipment as it provides adequate ventilation with sufficient electrical shielding.

Figure 6 illustrates the results secured with military specification type open terminal strips which are typical of those used in industrial 440V connections. Sustained arcs could only be secured under the conditions of three phase supply and with currents larger than 400 peak amperes. Equipment limitations were such that the maximum current was limited to 1500 amperes peak. It is believed that only sustained arcs provide a possibility of significant damage. The high levels of exposure required for these terminal strips, when coupled with the low transfer function which exists in most NEMA electrical enclosures, indicates that there is no serious industrial problem. When cooling air is forced through specific special case designs,each must be individually evaluated to determine whether a serious hazard exists. For the terminals shown the barrier strips insure that single fibers cannot individually bridge contacts. The alleviating effect of this will be covered later in this paper. In our experiments local damage to screwheads occurred and eventually fuses or breakers opened, and it is believed that similar experience would be encountered in any protected industrial circuit.

A number of representative results have been correlated in Figure 7. As was indicated by the previous listing, most consumer goods, 110V equipment and most avionics were found to be not vulnerable. The most vulnerable equipment, not reported herein, was equipment of 1950-1960 vintage, generally of high impedance and tested with high modulus fibers. At the time these tests were performed it was not known what the range of fire-emitted lengths would be. The test results which were secured over a range of fiber length, and which are typical of those used in the NASA risk analysis, are diagrammed in the remainder of the chart. There were no experimental points for any apparatus below the solid boundary line. The equation for this boundary is:

$$\overline{E} = 2 \times 10^7 \, (1/\ell)^2$$

This lower boundary is formed primarily by fan-cooled, nonfiltered equipment and by open terminal strips. For these there is no protection provided by the equipment case, or the forced airflow greatly enhances the number of fibers available to produce damage inside the case. All other failures are located to the right of this boundary. The demonstrated lower vulnerability is caused by case protection, the width of contact spacing, the invulnerability of specific types of circuitry or combinations of these factors. It should be emphasized that most of this testing was done with T-300 or equivalent fibers such as are now employed in aircraft construction. A partial tabulation of many of the tests is given in Table 1. Where no failures are shown the $\overline{E}$ values are the maximum values to which the equipment was subjected.

Fiber resistivity also potentially can affect equipment sensitivity. Figure 8 shows the result of probing the same amplifier with a fiber simulator which duplicates the contact resistance and burnout characteristics of a fiber. In the range of 3 to 7 mm contact gap lengths there were approximately 35 failure nodes with T-300, and about one tenth that number with DE-114. DE-114 is an experimental fiber produced primarily for its high resistivity. The actual average exposures to failure are shown on Figure 9. There is somewhat over one order of magnitude change in vulnerability shown in the tests done

with fiber on the test amplifier in the test chamber. This agrees well with the results secured by the probe. Two other pieces of equipment were also tested with fibers of differing resistivity. No probe testing was done on these more complicated circuits; however, the effect of resistivity is clearly shown. The relative slopes are greatly dependent on the separations of nodes and on the specific fiber resistivity. The large variation in the vulnerability of the color TV and transponder was not expected for the less than 3:1 ratio of resistances of the fiber types. Insufficient work has been done to be able to predict the slope of the vulnerability curve against fiber resistance for various classes of equipment.

In order to determine whether fire-released fibers would affect equipment in a manner similar to those used for chamber testing a series of tests was run at the Naval Surface Weapons Center, Dahlgren, Virginia. These tests will be discussed in detail in a later talk. Figure 10 diagrams the results of these tests. Six amplifiers were exposed to soot alone, as a control, to determine whether failures would occur, or affect the vulnerability of the equipment. Two amplifiers failed, one during soot exposure and one subsequently. A detailed examination of the failed equipment could not determine whether the cause was soot or not. The remaining four amplifiers were evaluated in the Aberdeen test chamber. The average exposure to failure was 0.8×10^6 for these tests. The change, if any, from the average exposure determined previously with 3 mm fibers, 2×10^6, is considered insignificant and is probably caused by normal statistical spread.

In a repeat test wherein graphite composite was burned at Dahlgren six amplifiers were again exposed. All of the amplifiers failed subsequent to an exposure of 5×10^6. At this exposure (measured by an electrical grid which detected 2 mm and longer fibers) it would be predicted that 6 failures would occur as shown on Figure 11. It may be concluded that the fire-released fibers have at least the same damage potential as the fibers used for chamber testing. Figure 12 further substantiates this point. Resistivity measurements were made of fibers released from fires at Dahlgren and during full-scale fire tests made at Dugway. This was accomplished with a wire-grid instrument wherein the voltage-current characteristics of each fiber that intersected the grid was determined. A continuous measurement was made of each fiber until fiber burnout occurred. The resistivity, when compared to the average resistance of virgin cut fiber, is essentially unchanged. Other data presented at this meeting indicates that measured diameters of fibers are smaller than pre-fire diameter. The data shows that there is a high correlation between fire-induced diameter reduction and small fiber length so that the wire grid would not detect most of the fibers of smaller diameters and short lengths. The long high-resistance tail on the distribution plot indicates that a small number of decreased diameter fibers may have been encountered.

Figure 13 outlines the test flow for commercial avionics. In this test series it was important to ascertain whether the flight environment subsequent to graphite fiber exposure could introduce failures by redistribution of trapped fibers. Each device was subjected to an exploratory vulnerability test to determine if detailed testing was warranted. Three exposures to $\bar{E} = 3 \times 10^7$, without intermediate cleaning, and with simulated environment after each

exposure were used. If the equipment did not fail, testing was terminated as the exposure to 9 x 10^7 was sufficient indication of invulnerability. If a failure occurred at any fiber length,four tests were run as indicated with no cleaning between the tests which were made at increasing levels of exposure. The results of this sequence are shown on Figure 14. It is interesting to note that for this equipment, tested under simulated landing shocks and 100 db of white acoustic noise, that five of the fifteen failures occurred during simulated environment. The average exposures to failure for this equipment as used in the NASA risk analysis included the effect of environment as demonstrated in these tests.

A limited number of tests, not reported herein, attempted to simulate the post-exposure experience of turning ground-based equipment on and off, and of moving the equipment. In no case were failures encountered subsequent to the fiber exposure period in the test chamber.

One other facet of aviation risk was investigated analytically to determine if a sufficient hazard exists to require some precautionary action. The effect of a graphite fiber cloud on existing and proposed terminal landing aids was evaluated. Figure 15 outlines the results secured on the 300 MHz glide slope equipment now in use and on the planned 5 GHz microwave landing systems (MLS) scanning antenna systems which will be deployed as per present FAA planning. There is no effect of concern on the glide slope equipment as attenuation effects are negligible, nor is there any problem with differential attentuation of the beams from the two antennas used in this system. For the MLS there is appreciable attenuation of the beam only in the very conservative case of the beam traveling through the entire length of the fire-ejected plume into the aircraft antenna. Even in this worst case the specified capability for the system insures that the range is not below 17 kilometers, which is still adequate. If the signal strength is below acceptable limits in the aircraft for any cause the pilot is warned by a display flag and will disregard the display until signal strength is adequate. It is most probable that during normal controlled operations the aircraft would be diverted or delayed if the fire plume really occupied the direct landing environment of the airport.

The ground based equipment which generates the ILS and MLS signals is well protected, both by air-conditioned building enclosures and by specific filtering of cooling air entering the equipment racks so that there is no concern with interfering with the ground based equipment.

The shock hazard potential of graphite fibers has been investigated for a large number of consumer electrical items. A detailed report on method and results will be presented tomorrow by the National Bureau of Standards. Data extracted from their report is presented herein in order to approximately evaluate the magnitude of the danger nationally. Figure 16 lists all of the items considered a potential hazard by the NBS and subsequently tested in the BRL test chambers. Six items were tested. The toaster, because of the number in use, and the highest vulnerability to case shorts was selected for detailed testing. It is believed that there is no appreciable national risk compared to the toaster from the other five items. Figure 17 presents the results of the tests made on 6 toasters over a fiber length range of 1 to 12 mm. While

the absolute values are different for each unit, the curve shapes are all similar and follow a characteristic inverse E vs length relationship. For the smaller length fibers such as may be released from a fire the equation

$$\bar{E} = 5 \times 10^8 \; (1/\ell)^3$$

provides a good fit to all of the data.

To provide a sample computation for the national risk the shorting probability versus exposure relationship must be ascertained. Figure 18 shows these relationships for toaster #6 for each of three fiber lengths. While the 3 mm and 10 mm experimental points follow an exponential failure curve, as would be expected when bridging can be accomplished by a single fiber, the experimental points for the 7 mm fibers are an indication that multiple fibers are required to produce a short. Similar results were secured for other lengths in other toasters, particularly for the shorter fiber lengths. The use of simple exponential failure laws for these cases will overestimate the risk for low exposures. It is difficult to evaluate the magnitude of the overestimate without taking large numbers of data points to better define the damage curves at low exposures. Because of this, and because the computation will always produce conservative answers the exponential failure law has been applied throughout the risk analysis and will be used for the shock hazard approximation.

In order to integrate the effects of a fiber spectrum so that equipment vulnerability in a fire can be evaluated it is necessary to summate the damage potential for all lengths. Figures 19 and 20 indicate the two methods by which this can be accomplished. In the detailed stepwise integration method it is necessary to find the exposure at each length and divide by the $\bar{E}$, the average E for damage for that length. An overall summation across the length spectrum then provides an expression for the probability of damage; for a normalized quantity of fibers

$$P_D = 1 - e^{-\int_0^\infty \frac{F(\ell)d\ell}{\bar{E}}}$$

If the length spectrum and damage relationships can be expressed as simple exponentials or power laws it is possible to derive analytic expressions for the overall integrals as shown in Figure 20. Dr. W. Elber has derived closed form relationships which express these integrals for various exponents of the damage curve and for various values of the average fiber length, ℓ_a. For the case shown where E is proportional to $(1/\ell)^2$ he has shown that an equivalent E can be used which is the E that occurs at $\sqrt{2}\;\ell_a$. For the case where $\bar{E}$ varies as $(1/\ell)^3$ the equivalent E occurs at $\ell = 1.8\;\ell_a$. This relationship is used in this paper and has been used to simplify the national risk analyses which will be presented in later papers. For most of the fire data to date average fiber lengths have been about 2 millimeters, so that computations presented herein will be based upon the E values which have been secured with 3 mm test fibers. An increase of average length to 3 mm would increase the E estimate by a factor of three, and the overall risk estimate by a factor of two (because of the smaller number of fibers per unit mass release).

The sample computation is shown in Figure 21. The assumptions are that 1000 kilograms of fiber are involved in each of 5 fire related accidents per year, that 1% of the mass is released and could enter homes having average transfer-functions of .01. The population and toaster density, 330 per square kilometer is typical of a densely populated city and all of the fibers are assumed to land in that area. The results of tests performed on six toasters, reported in detail in CR 159147 show that the E for 3 mm fibers for the average toaster is 2×10^7 fiber seconds/meter^3. The tests also indicated that, in only 16 of 25 tests did the voltage to the case exceed 60 volts. In addition, when the toaster was energized, in only 3 of 25 tests was the fiber retained long enough to allow a measurement of current carrying capability. In these measurements the maximum current carried was 10 milliamps. When this data is substituted in the equation shown, the computed probability of a potential hazard is 0.38/year. This is not a large hazard (Figure 22) and is probably excessively conservative in that it ignores the multi-fiber failure relationship, and the statistics connected with the distribution of user resistance to ground. Finally the currents which were maintained below 10 milliamps could produce shock sensations and secondary injury but could not themselves be more than an annoyance.

The last figure (Figure 23) outlines the conclusions drawn from the data presented. The data collected and analyzed has been used in the NASA National Risk Analysis which will be presented in a following paper. While the data is restricted to T-300 or similar fibers it is believed that structural materials would have similar properties. Extensions of these data to other fibers having different resistances or fall rates is not warranted.

The characteristics of fire-released fibers have been measured, both by direct measurement in fire plumes and indirectly by exposing equipment to a fire plume. The damage potential to electrical equipment does not change materially because of the fire.

The failure rates for avionics equipment are influenced by post exposure environmental conditions. These effects have been taken into account in the national risk estimate.

There is a negligible shock hazard in a small number of home appliances. The national risk is small and can in no case result in a hazard to life with the test fibers used.

A final word about repairs. In almost all cases failures were cleared by simple vacuuming of the equipment. Where damage to components occurred it was not caused by the limited energy-dissipation characteristics of the fiber, but rather by upsetting a control circuit, or in the case of three phase arcs, by initiating an energy release almost independent of the fiber characteristics. For other than 3 phase industrial equipment, where downtime costs may predominate, the major cost encountered would be those costs associated with examining and cleaning rather than replacing components in the equipment.

TABLE 1.- SUMMARY OF VULNERABILITY TESTING FOR ELECTRICAL EQUIPMENT

ITEM	FACILITY	TEST MATERIAL	LENGTH	$\overline{E}$	# of TESTS	REMARKS
Power Supply	LaRC	Thornell 300	8.0	1.0×10^8	1	No Failures
Wall Socket	LaRC	Thornell 300	3	3.0×10^8	4	
			7	8.0×10^7	4	
			16	4.0×10^8	4	
Quick Disconnect Terminals	RADC	GY 70	3	$.6 \times 10^7$	6	0.635 cm (0.25 in.) Spacing
			7	$.3 \times 10^6$		
			12	$.2 \times 10^6$		
			3	$.2 \times 10^9$		1.905 cm (0.75 in.) Spacing
			7	$.2 \times 10^7$	6	
			12	$.5 \times 10^6$		
			3	$.4 \times 10^9$		1.27 cm (0.5 in.) Spacing
			7	$.1 \times 10^8$		
			12	$.1 \times 10^7$	6	
Gen'l Aviation Type Distance Measuring Transponder (DME)	BRL	AS	1	5.7×10^8	2	No Failures
			3.5	5.4×10^7	3	No Failures
			7	6.7×10^7	2	No Failures
Amplifier, Audio Power, 410	BRL	Thornell 300	2.5	2.5×10^6	4	
			7.5	5.0×10^5	4	
			14.5	3.0×10^4	4	
Calculator/Printer	BRL	AS	20	3.9×10^7	1	No Failure
		Thornell 300	1.3	5.9×10^8	4	No Failure
		Thornell 300	2.1	3.5×10^8	2	No Failure
			8.0	3.2×10^7	4	No Failure
			20	3.3×10^7	2	No Failure

TABLE 1.- Continued

ITEM	FACILITY	TEST MATERIAL	LENGTH	E	# of TESTS	REMARKS
Computer, MOS	BRL	Thornell 300	1.3	1.5×10^7	2	No Failure
Open Circuit Board		Thornell 300	1.3	5.0×10^7	3	No Failure
			4	7.4×10^7	2	No Failure
			4	1.2×10^6	2	No Failure
Computer	BRL	HMS	1	8.9×10^6	9	No Failure, Off Mode
			1	1.0×10^8 Est.	3	
			1.7	1.6×10^6	7	
			3.5	2.9×10^7	1	Off Mode
			4.7	5.6×10^5	5	
			7.8	3.3×10^5	10	
			8	5.0×10^6 Est.	10	Off Mode
Dishwasher	BRL	HMS	3.5	1.0×10^8	3	No Failure, Off Mode
			7.5	6.0×10^7	3	No Failure, Off Mode
			10	4.5×10^7	2	No Failure, Off Mode
Dryer, Clothes	BRL	HMS	3.5	6.0×10^7	3	No Failure, Off Mode
			7.5	6.5×10^7	10	No Failure, Off Mode
			10	3.0×10^7	5	No Failure, Off Mode
Heater, 1500 Watt Electric	BRL	HMS	3.5	1.0×10^8	7	No Failure, Off Mode
			7.5	6.0×10^7	10	No Failure, Off Mode
			10	4.5×10^7	9	No Failure, Off Mode
Iron, Hand	BRL	HMS	3.5	6.0×10^7	3	No Failure, Off Mode
			7.5	6.5×10^7	9	No Failure, Off Mode
			10	3.0×10^7	6	No Failure, Off Mode
Food Mixer, Hand #1	BRL	HMS	3	1.0×10^8	3	No Failure, Off Mode
			7.5	6.0×10^7	3	No Failure, Off Mode
			10	4.5×10^7	4	No Failure, Off Mode

TABLE 1.- Continued

ITEM	FACILITY	TEST MATERIAL	LENGTH	$\bar{E}$	# of TESTS	REMARKS
Food Mixer, Hand #2	BRL	HMS	3	6.0×10^7	4	No Failure, Off Mode
			7.5	6.6×10^7	4	No Failure, Off Mode
			10	3.0×10^7	2	No Failure, Off Mode
Microwave Oven #1	BRL	Thornell 300	1	8.1×10^7	2	No Failure, Off (Clock On)
			4	5.0×10^6 Est.*	2	No Failure, On & Off
			4	3.5×10^7	3	Off, (Clock On)
			4	6.0×10^6	1	On, Low Power
			10	6.6×10^6	1	Low Power
Microwave Oven #2	BRL	HMS	3.5	1.0×10^8	4	No Failure, Off Mode
			7.5	6.0×10^7	5	No Failure, Off Mode
			10	4.5×10^7	2	No Failure, Off Mode
Radio, Clock	BRL	HMS	2.5	2.0×10^8	4	No Failure, FM
			2.5	3.2×10^8	6	No Failure, Off Mode
			7.5	4.0×10^7	3	No Failure, FM
			7.5	1.1×10^8	4	No Failure, Off Mode
			15	1.1×10^8	4	No Failure, Off Mode
Radio, Portable	BRL	Thornell 300	2.5	1.9×10^8	3	No Failure, FM
			7.5	1.1×10^8	3	No Failure, FM
			7.5	6.4×10^7	2	No Failure, Off Mode
			15	7.5×10^7	3	No Failure, FM
Radio Receiver, AM-FM	BRL	Thornell 300	2.5	2.0×10^8	3	No Failure, FM
			7.5	1.9×10^8	5	FM
			15	5.7×10^7	3	No Failure, FM

TABLE 1.- Continued

ITEM	FACILITY	TEST MATERIAL	LENGTH	$\overline{E}$	# of TESTS	REMARKS
Tape Recorder, Portable	BRL	Thornell 300	2.5	1.3×10^8	2	No Failure, Record to Off
		Thornell 300	2.5	1.5×10^8	2	No Failure, Record to Off
		Thornell 300	7.5	2.0×10^8	4	No Failure, Record to Off
		Thornell 300	7.5	8.3×10^7	2	No Failure, Off Mode
		Thornell 300	14.5	1.2×10^8	4	No Failure, Record to Off
Tape Recorder, AC or Portable	BRL	Thornell 300	2.5	7.5×10^7	3	No Failure, Record to Off
			7.5	1.1×10^8	3	No Failure, Record to Off
			15	1.9×10^8	3	No Failure, Record to Off
Cash Register	BRL	Thornell 300	2.5	1.1×10^8	2	No Failure. On Memory
			7.5	1.4×10^8	4	No Failure. ON
			7.5	3.7×10^7	2	No Failure. Overnite Standby
			15	6.3×10^7	2	No Failure. ON
			15	3.8×10^7	2	No Failure. On Memory
Stereo System	BRL	Thornell 300 unsz	2.5	2.2×10^8	3	No Failure. On, FM Stereo
			7.5	2.2×10^8	5	No Failure. On, FM Stereo
			15	5.7×10^7	3	No Failure. On, FM Stereo
Telecopier	BRL	Thornell 300	2.5	1.1×10^8	3	No Failure, Off Mode
		H_2O sz	7.5	4.0×10^7	3	No Failure, Off Mode
			14.5	6.8×10^7	2	No Failure, Off Mode

TABLE 1.- Continued

ITEM	FACILITY	TEST MATERIAL	LENGTH	$\overline{E}$	# of TESTS	REMARKS
Television, B&W 16"	BRL	HMS	3.5	4.3×10^6	1	No Failure
			3.5	5.9×10^7	1	No Failure, Off Mode
			7	9.6×10^7	3	No Failure,
			7	1.8×10^7	1	No Failure, Off Mode
			7	4.2×10^7	1	No Failure, Back Cover Removed
Television, B&W 19"	BRL	Thornell 300	1	2.3×10^8	3	No Failure, Off Mode
			2.5	4.8×10^7	3	
			2.5	1.4×10^8	2	No Failure, Off Mode
			7.5	1.1×10^7	4	
			7.5	1.1×10^8	3	No Failure, Off Mode
			16	6.8×10^7	2	No Failure
Television, Color 19"	BRL	AS	20	6.6×10^7	2	
		HMS	8	6.7×10^6	5	
		Thornell 300	8	4.7×10^7	4	
		Thornell 300	20	3.9×10^5	1	No Failure
		Thornell 300	1.3	5.9×10^8	1	
		Thornell 300	2.1	3.5×10^8	2	No Failure
		Thornell 300	8	8.0×10^6	4	
		Thornell 300	7.5	1.2×10^7	5	Back Cover Removed
Television, Color 25"	BRL	Thornell 300	2.5	1.1×10^8	2	
			7.5	1.2×10^8	4	No Failure
			7.5	6.1×10^7	2	No Failure, Off Mode
			15	2.5×10^7	4	
Terminal, Telephone	BRL	Thornell 300	1.3	8.0×10^6	3	Frequent Recall by Keying
			4	1.7×10^7	2	Frequent Recall by Keying

TABLE 1.- Continued

ITEM	FACILITY	TEST MATERIAL	LENGTH	$\overline{E}$	# of TESTS	REMARKS
Terminal, Video	BRL	Thornell 300	1 4 4 10	8.1×10^7 5.1×10^7 4.3×10^7 6.6×10^6	2 4 2 1	Writing & Scrolling Writing & Scrolling Off Mode Writing and Scrolling All 4-No Failure
Thermostat, (Millivolt)	BRL	HMS	7 7	5.7×10^7 1.2×10^7	3 1	No Failure, Open No Failure, Open No Cover
Thermostat, 24 VAC	BRL	HMS	7 7	5.7×10^7 1.2×10^7	3 1	No Failure, Open 24 VAC Applied No Failure, Open 24 VAC Applied, No Cover
Thermostat, 110 VAC	BRL	HMS	7	6.9×10^7	4	No Failure, Open 110 VAC Applied
Toaster-Oven #1	BRL	HMS	3.5 7.5 10	1.0×10^8 6.0×10^7 4.5×10^7	3 6 9	No Failure, Off Mode No Failure, Off Mode No Failure, Off Mode
Toaster-Oven #2	BRL	HMS	3.5 7.5 10	6.0×10^7 6.6×10^7 3.1×10^7	3 6 2	No Failure, Off Mode No Failure, Off Mode No Failure, Off Mode
Vacuum, Upright	BRL	HMS	3.5 7.5 10	1.0×10^8 6.0×10^7 4.5×10^7	3 3 2	No Failure, Off Mode No Failure, Off Mode No Failure, Off Mode

TABLE 1.- Continued

ITEM	FACILITY	TEST MATERIAL	LENGTH	$\overline{E}$	# of TESTS	REMARKS
Valve, Gas, (Millivolt)	BRL	HMS	7	6.9×10^7	4	No Failure, Closed
Valve, Gas (24 VAC)	BRL	HMS	7	6.9×10^7	4	No Failure, Closed
Transponder, General Aviation	BRL	AS	3.5 7.0 15.0	$.96 \times 10^8$ 1.0×10^8 2.4×10^8	12 12 12	Three Failures Two Failures One Failure
ASR-3 Transmitter Cabinet	BRL	HMS	7.5 10.0 7.5	9.3×10^7 1.5×10^7 3.02×10^6	4 1 5	No Failure with Filter No Failure with Filter 5 Failures, without Filters
ASR-3 Receiver Cabinet	BRL	HMS	7.5 7.5	5.04×10^7 7.8×10^5	8 8	4 Failures, with Filters 8 Failures, without Filters

TABLE 1.- Concluded

ITEM	FACILITY	TEST MATERIAL	LENGTH	$\bar{E}$	# of TESTS	REMARKS
ATC Transponder*	LaRC	Thornell 300	1 3 10	5.5×10^7 3.7×10^6 1.6×10^7	5 5 5	3 Failures 5 Failures 5 Failures
VHF Transceiver*	LaRC	Thornell 300	1 3 10	9×10^7 3×10^7 9×10^7	1 4 1	No Failures No Failures No Failures
ILS Receiver*	LaRC	Thornell 300	1 3 10	9×10^7 9×10^7 9×10^7	1 1 1	No Failures No Failures No Failures
D.M.E.*	LaRC	Thornell 300	1 3 10	9×10^7 3×10^7 9×10^7	1 4 1	No Failures No Failures No Failures
Flight Director*	LaRC	Thornell 300	1 3 10	9×10^7 3×10^7 6×10^7	1 4 4	No Failures 3 Failures 2 Failures

* Tests included exposure to simulated flight environments

- VULNERABILITY
- FACTORS AFFECTING VULNERABILITY
- SHOCK HAZARD EVALUATION
- CONCLUSIONS

Figure 1.- Vulnerability of equipment and shock hazards.

TEST CONDITIONS

A) T-300 OR EQUIVALENT FIBERS

B) LENGTHS FROM 1 TO 10 MILLIMETERS

C) LOW-TURBULENCE ROOM OR SIMULATED VENTILATION

D) EQUIPMENT OPERATING

E) MAXIMUM TEST EXPOSURES = 10^8

F) FOR AVIONICS ONLY - POST EXPOSURE ENVIRONMENTAL SIMULATION

Figure 2.- Equipment vulnerability and shock hazards.

WITH NO FAILURES

- TELECOMMUNICATOR
- BLACK & WHITE TELEVISION
- ASR 3
- CALCULATOR
- CALCULATOR & PRINTER
- TAPE RECORDER
- ELECTRIC MOTORS (6) 110 V.
- THERMOSTATS (2)
- CASH REGISTERS
- PORTABLE HEATER
- AM/FM RADIO
- HOME MUSIC SYSTEM
- CLOCK RADIO
- 10 BAND RADIO
- CAR RADIO
- TOASTERS
- ILS RECEIVER
- DME
- SMOKE ALARMS
- IRONS
- TOASTER OVEN
- FOOD MIXER

WITH FAILURES

- MISC. EQUIPMENT,
  - HIGH MODULUS FIBERS
  - RESTRICTED LENGTHS
- COMPUTER
- COLOR TELEVISION
- DIGITAL VOLTMETER
- ATC TRANSPONDER
- VHF TRANSCEIVER
- FLIGHT DIRECTOR
- CONNECTOR BLOCKS
- QUICK DISCONNECTS
- RELAYS
- GENERIC CIRCUITS
- POWER AMPLIFIER
- MICROWAVE OVEN

Figure 3.- Equipment tested in chamber.

WITH NO SIGNIFICANT FAILURES

- REFRIGERATORS
- FREEZERS
- RANGES
- DISHWASHERS
- CLOTHES WASHER
- CLOTHES DRYER
- VACUUM CLEANERS
- IRONS
- FRY PANS
- BED COVERS
- COFFEE MAKERS
- PERCOLATORS
- FOOD MIXERS
- CAN OPENERS
- PORTABLE HEATERS

WITH FAILURES

NONE

Figure 4.- Appliances tested with fiber simulator.

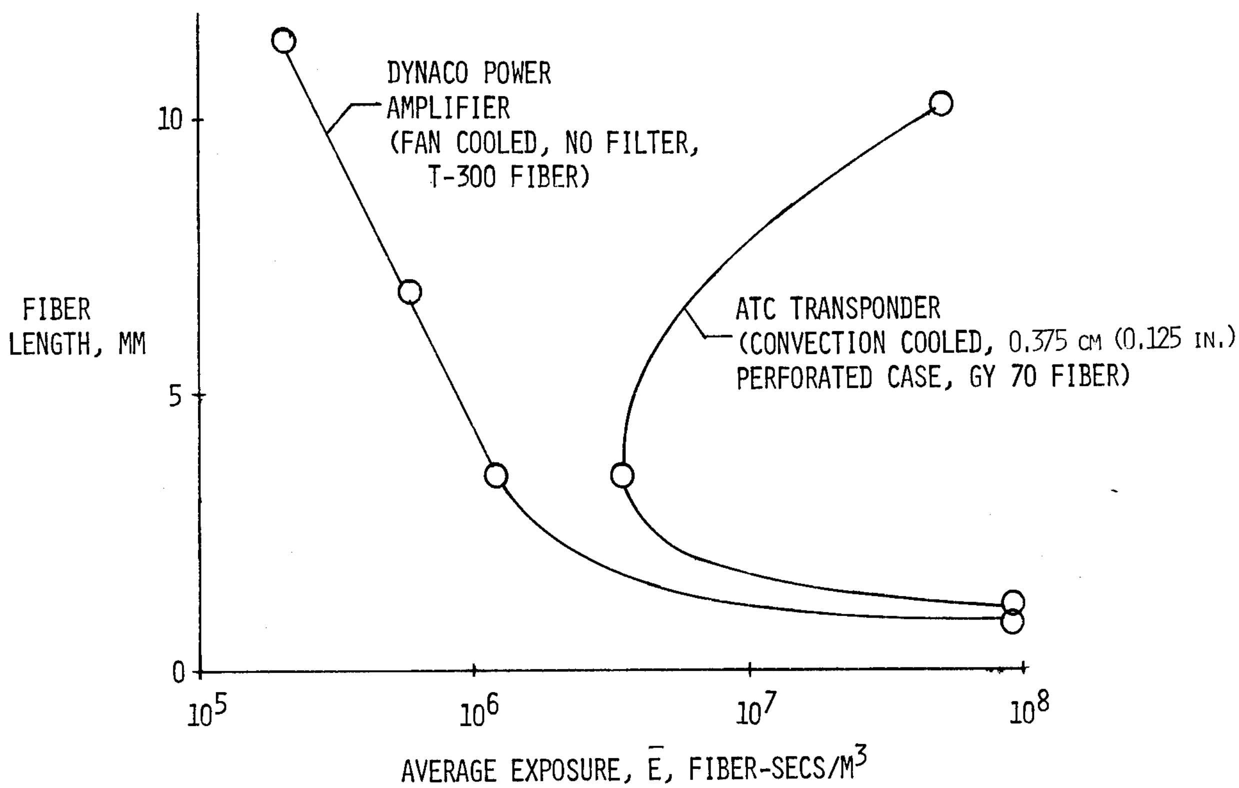
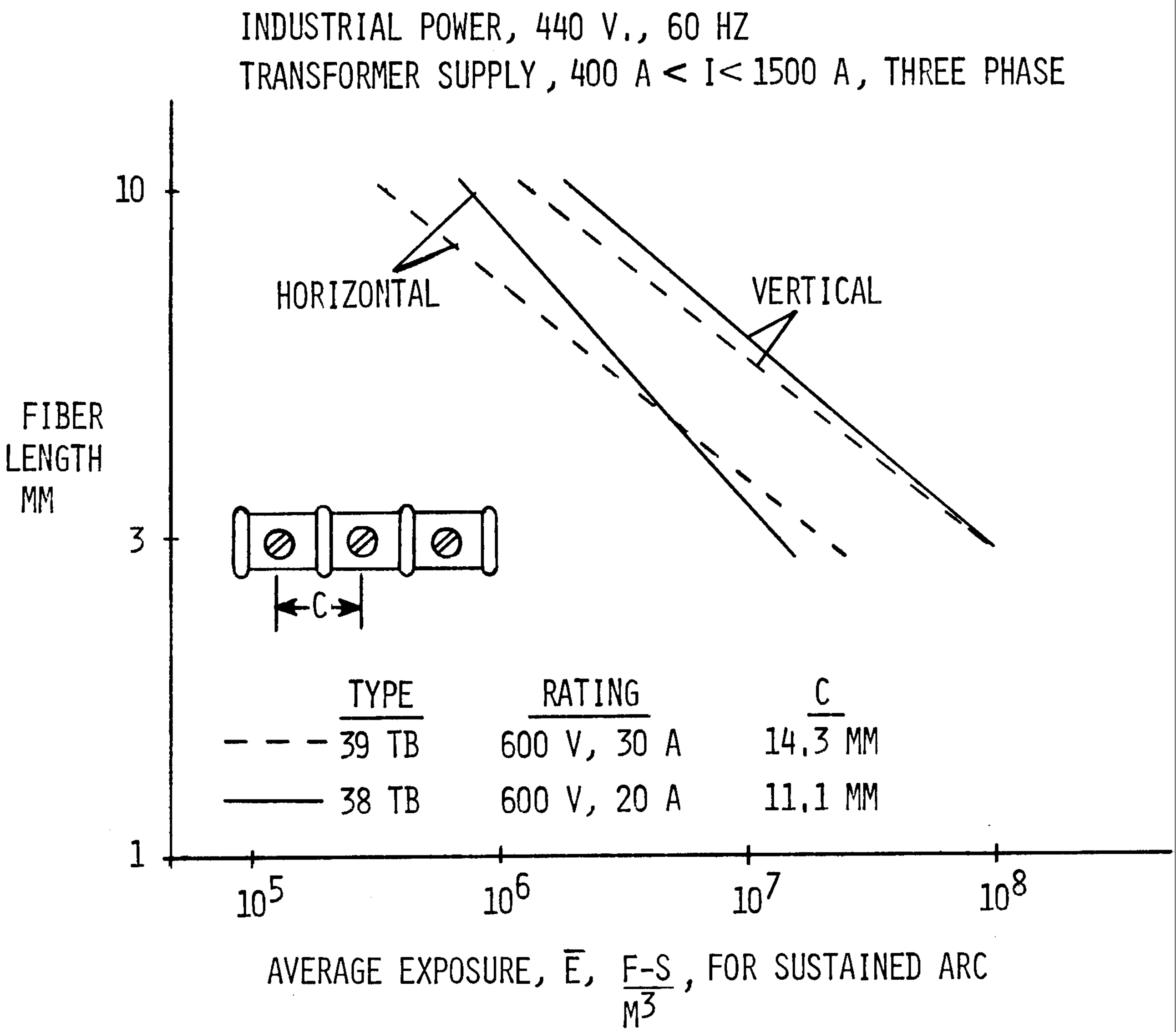


Figure 5.- Fiber length effect on equipment vulnerability.



NO SUSTAINED ARCS WITH SINGLE PHASE, TRANSFORMER SUPPLY, 440V, 60HZ

Figure 6.- Exposures for sustained arcs.

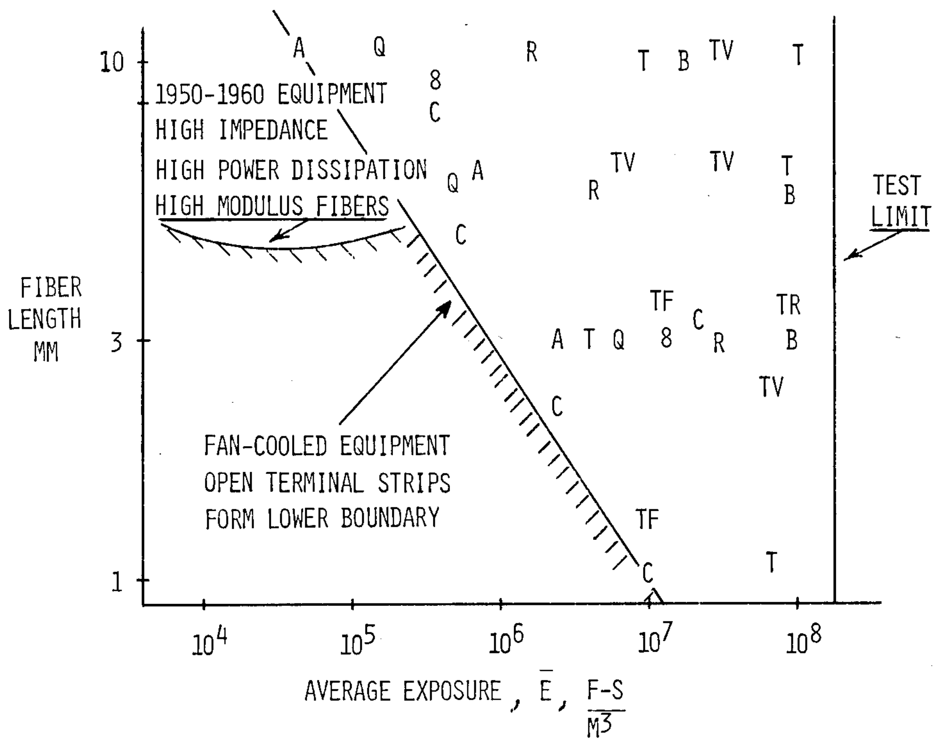


Figure 7.- Correlation of vulnerability with fiber length.

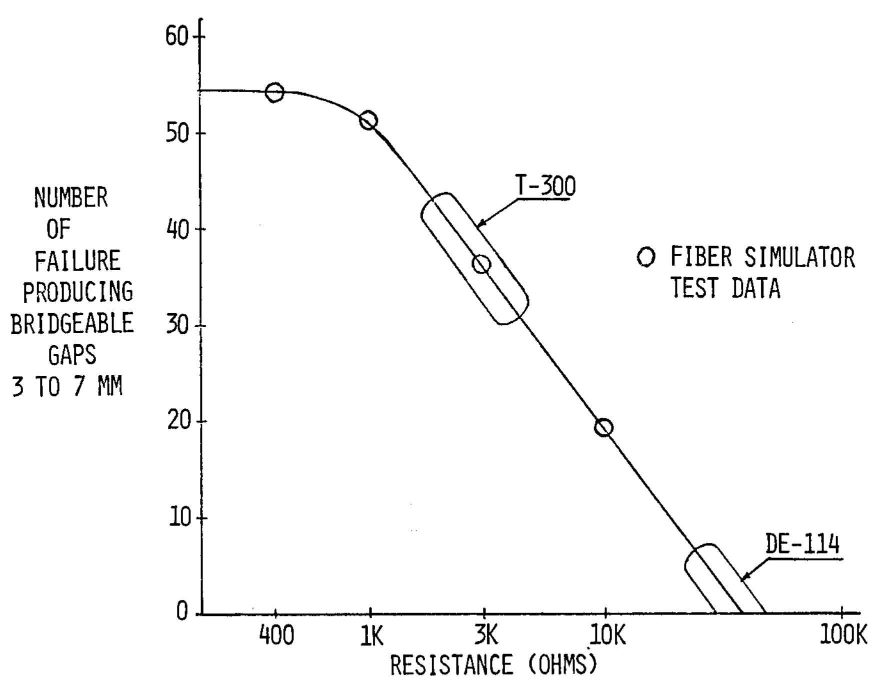


Figure 8.- Effect of fiber resistivity on Dynaco power amplifier.

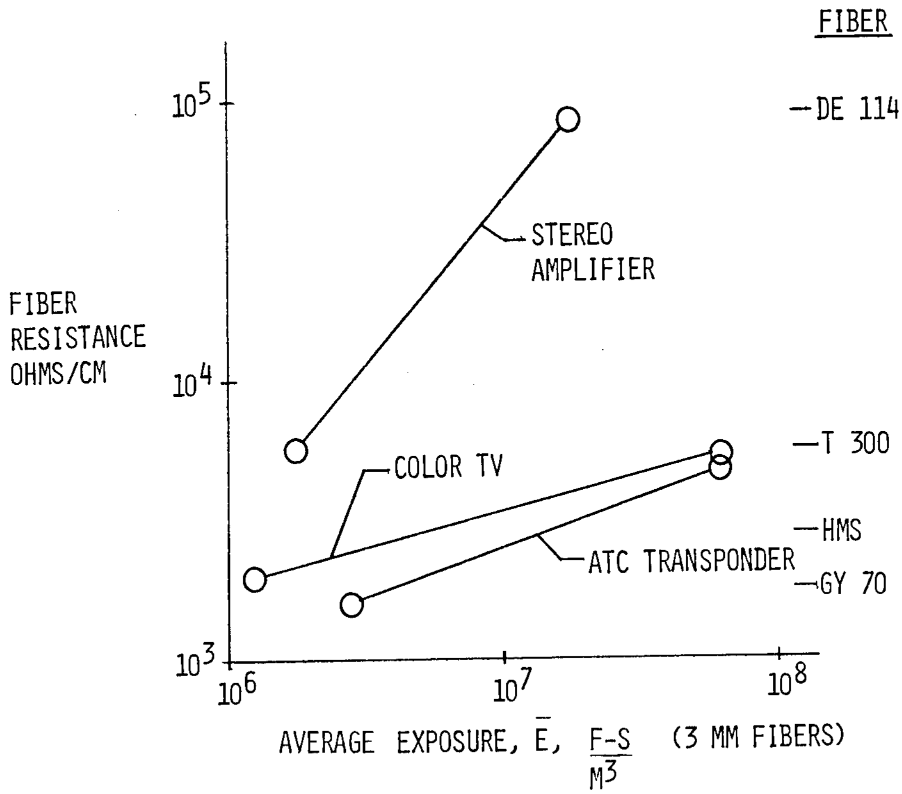


Figure 9.- Fiber resistance effect on equipment vulnerability.

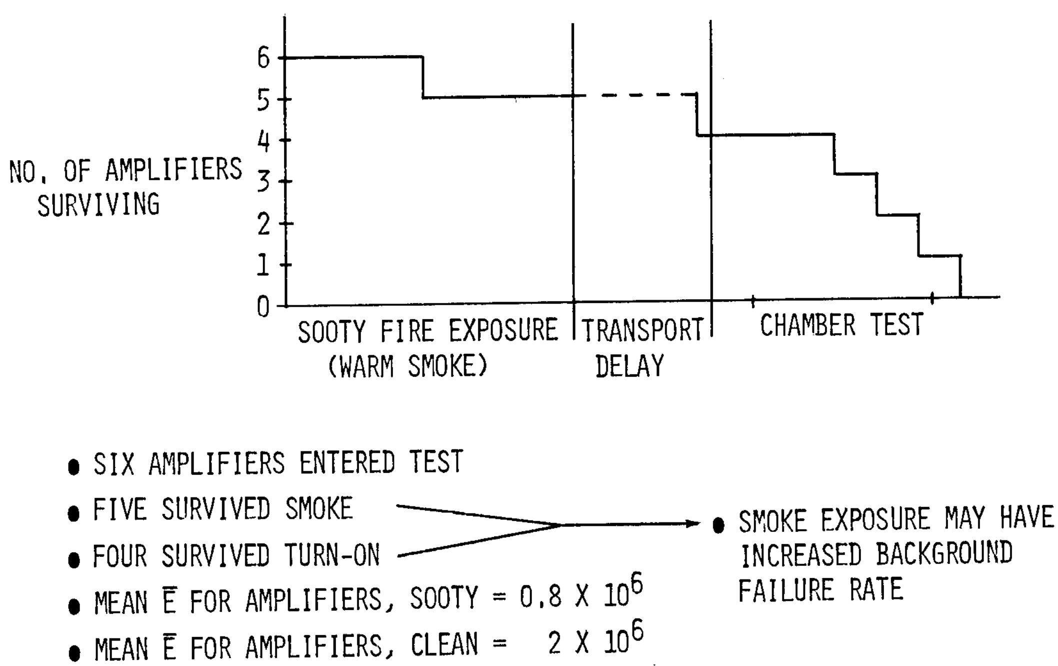


Figure 10.- Effect of soot exposure on Dynaco amplifiers.

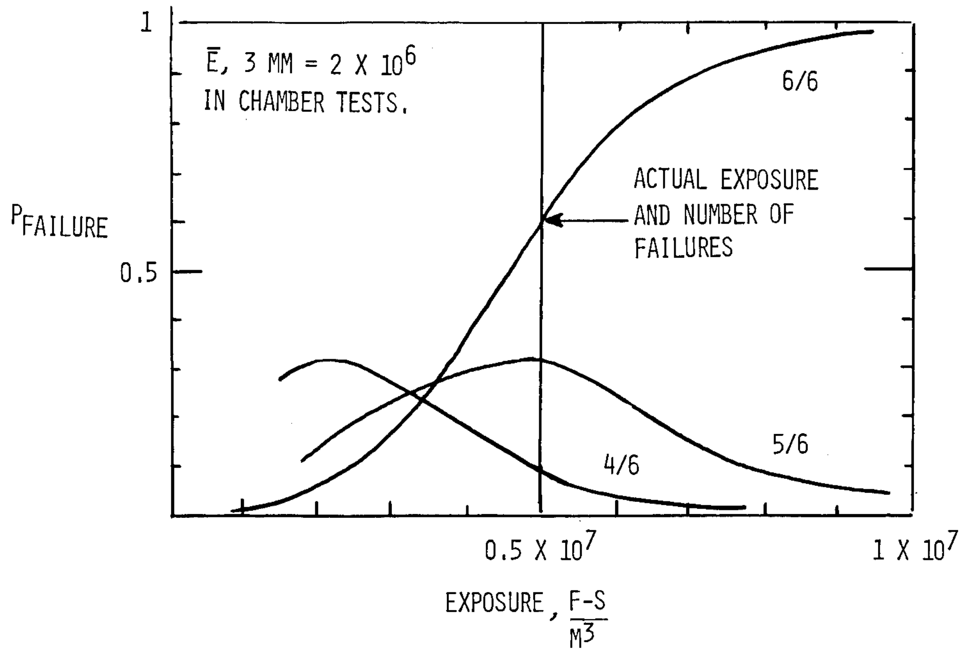


Figure 11.- Vulnerability of amplifiers to fire-released fiber.

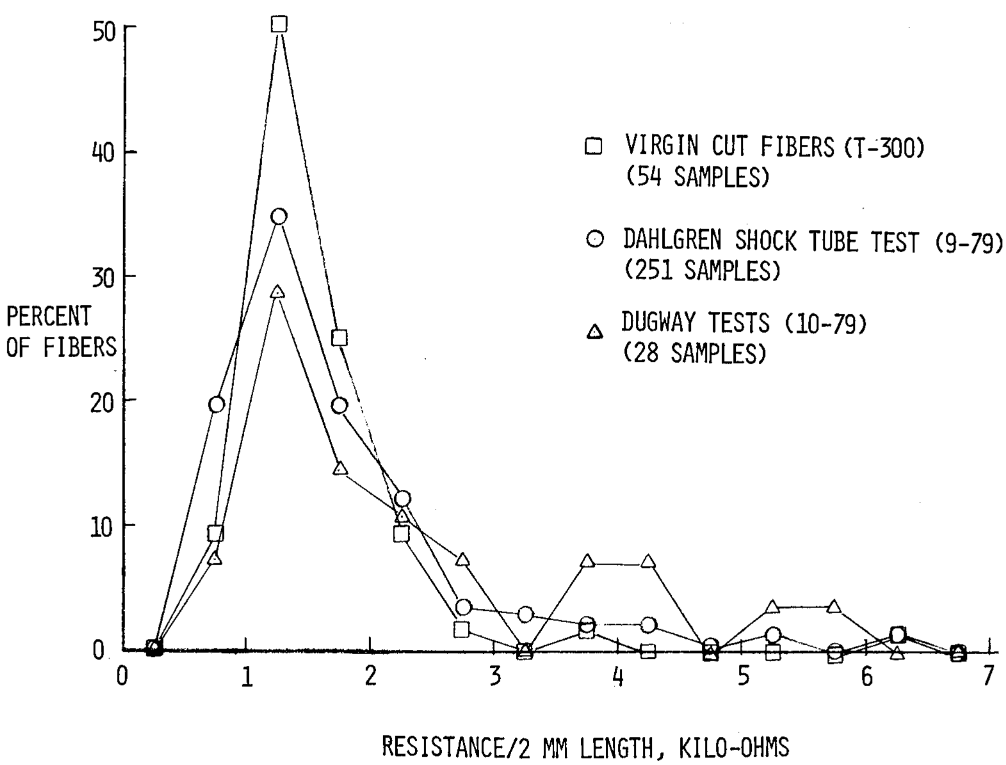


Figure 12.- Fire-released fiber resistivity.

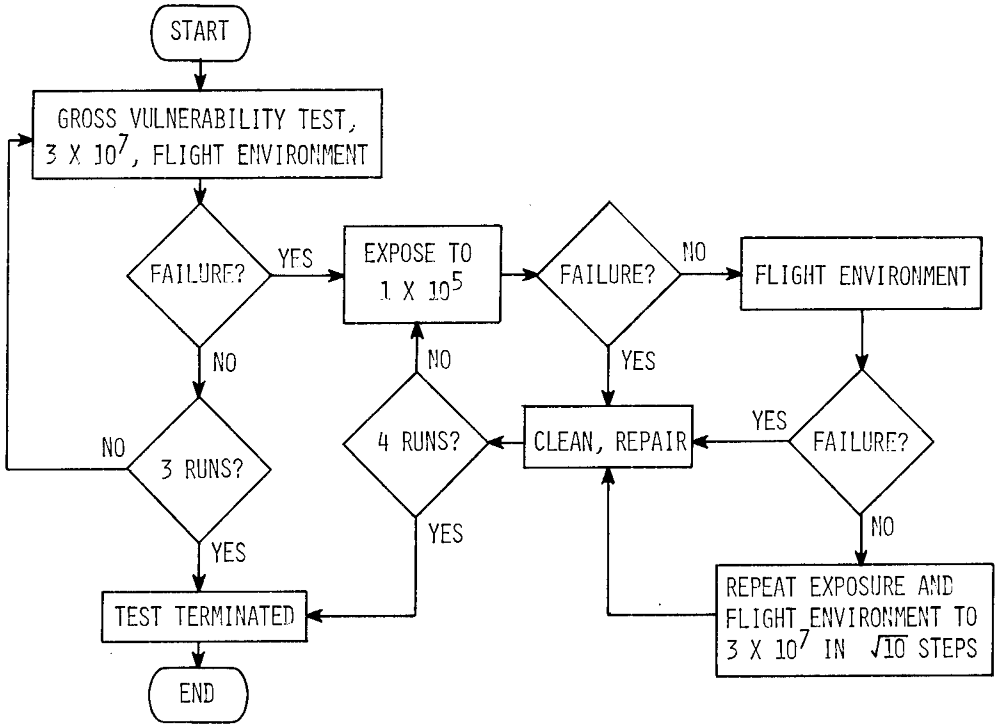


Figure 13.- Test method for avionics.

ITEM	FIBER LENGTH	FAILED EXPLORATORY TEST	EVALUATION TESTS		
			WITH NO FAILURE	FAILED DURING EXPOSURE	FAILED POST EXPOSURE
ILS RECEIVER	1	NO			
	3	NO			
	10	NO			
ATC TRANSPONDER	1	YES	2	2	-
	3	YES	-	3	1
	10	YES	-	4	-
DME	1	NO			
	3	YES	4	-	-
	10	NO			
FLIGHT DIRECTOR	1	NO			
	3	YES	1	1	2
	10	YES	2	-	2
VHF TRANSCEIVER	1	NO			
	3	YES	4	-	-
	10	NO			
			13	10	5

Figure 14.- Vulnerability of avionic equipment.

ASSUMPTIONS:

- 1000 KG FIRE
- 0.01 RELEASE, 3 MM FIBERS
- PLUME CROSS-SECTION - 100M X 100M
- BEAM INTERCEPTS TOTAL LENGTH OF PLUME

EFFECTS:

SYSTEM	FREQUENCY	ATTENUATION	EFFECT
I.L.S. (GLIDE-SLOPE)	330 MHZ	0.05 DB	NEGLIGIBLE
M.L.S. (SCANNING BEAM)	5 GHZ	5 DB	45% RANGE DECREASE (MIN. SPEC. RANGE = 37 KM)

Figure 15.- Graphite fiber effects on landing aids.

		FIBER LENGTH, MM		
		3	7	10
TOASTER	(6)	2×10^7	2×10^6	8×10^5
TOASTER OVEN	(2)	NONE	5×10^7	2×10^7
FOOD MIXER	(2)	7×10^7	NONE	3×10^7
HEATER		2×10^7	8×10^6	6×10^6
IRON		NONE	1×10^7	6×10^6
MICROWAVE OVEN		1×10^8	3×10^7	5×10^7

TOASTER IS THE GREATEST RISK
BECAUSE OF NUMBER IN USE AND VULNERABILITY

Figure 16.- Average exposures required to produce short to case.

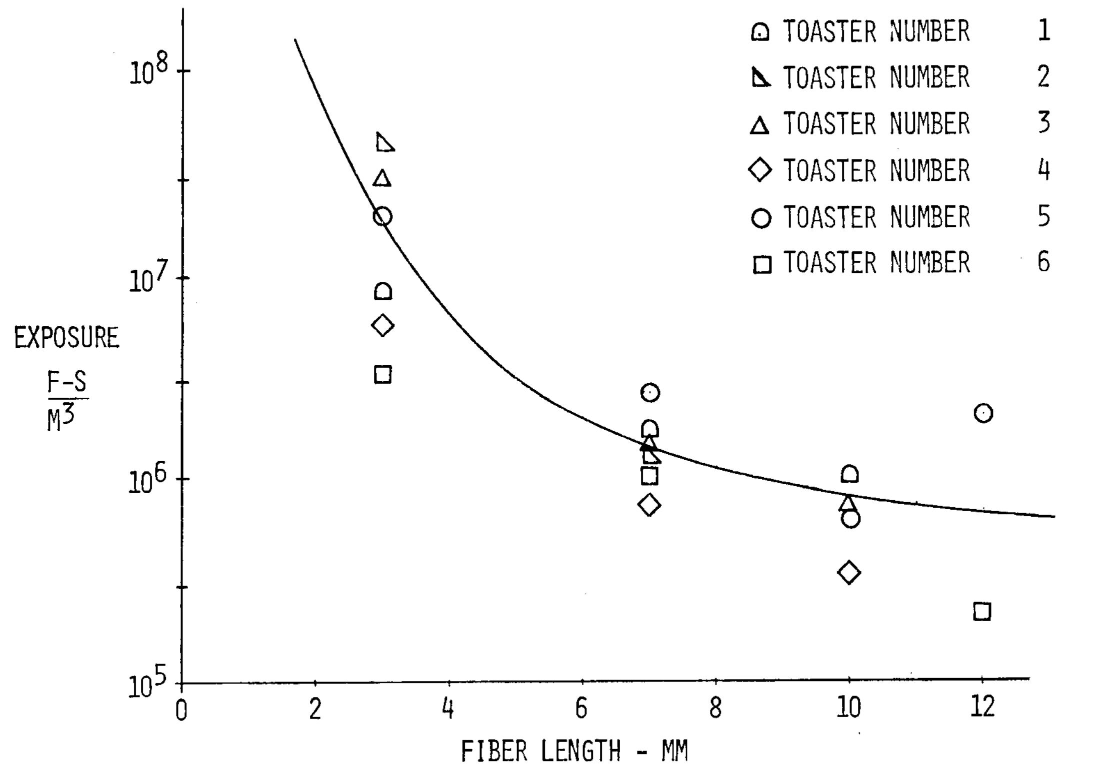


Figure 17.- Average exposure required for short to case of six toasters.

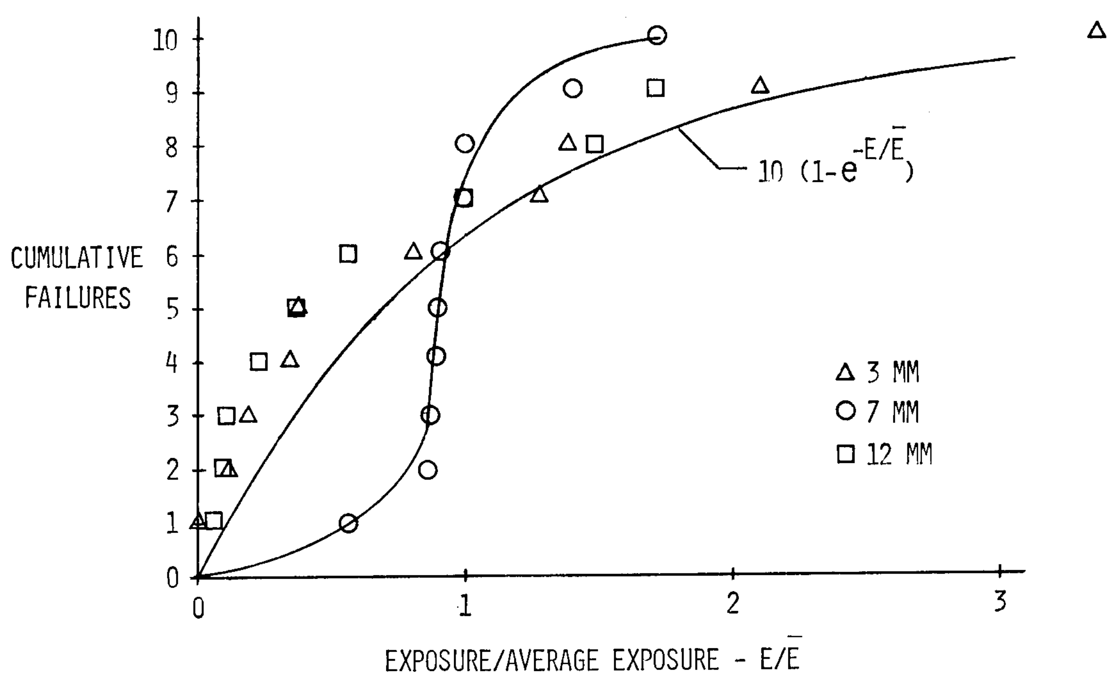


Figure 18.- Cumulative failure versus exposure toaster no. 6.

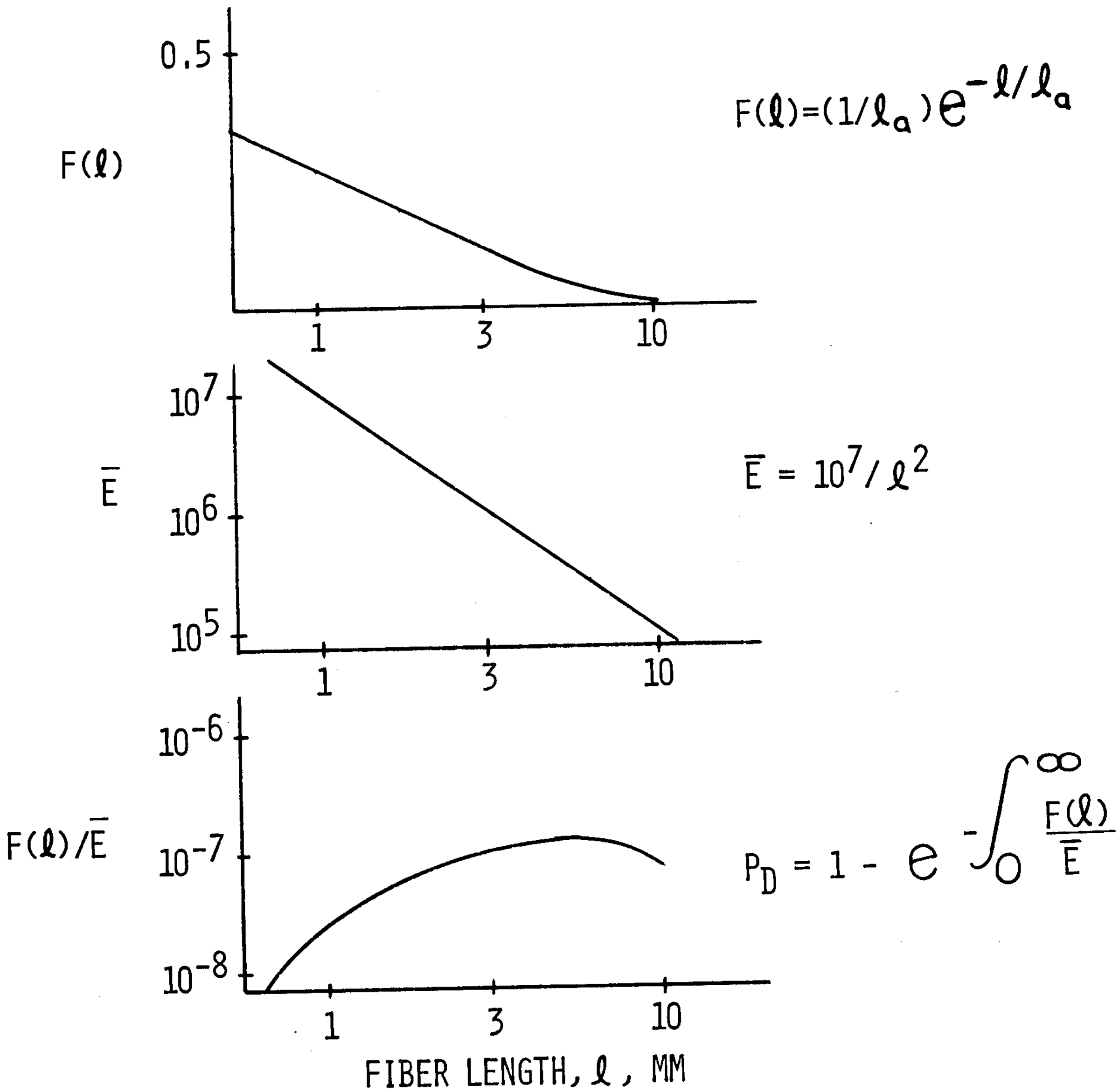


Figure 19.- Fiber length spectrum evaluation, detail integration.

1) ALL FIBERS OF LENGTH ℓ_a

2) EQUIVALENT EFFECTIVE $\bar{\bar{E}}$;
$\bar{\bar{E}}$ AT $\ell = \sqrt{2}$ TIMES AVERAGE LENGTH

3) $P_D = 1 - e^{E_{\ell_a}/\bar{\bar{E}}}$

Figure 20.- Fiber length spectrum evaluation, analytical.

ASSUMPTIONS

- 1000 KG IN EACH OF 5 ACCIDENTS/YEAR
- .01 FIRE RELEASE RATE
- 330 TOASTERS/KM^2
- TRANSFER FUNCTION, .01

EXPERIMENTAL RESULTS

- $\bar{E} = 2 \times 10^7$, 3 MM FIBERS
- VOLTAGE>60 V IN 16 OF 25 TESTS
- FIBER RETENTION IN 3 OF 25 TESTS
- $I_{MAX} \leq 10$ MA

$$P_{\substack{\text{POTENTIAL}\\\text{SHOCK}}} = \left[\frac{N}{U_S}\right]\left[\frac{\text{T.F.}}{\bar{E}}\right]\left[\frac{\text{TOASTERS}}{\text{AREA}}\right]\left[P_V > 60\right]\left[P_R\right]$$

$$P_{\substack{\text{POTENTIAL}\\\text{SHOCK}}} = 0.38/\text{YEAR}$$

Figure 21.- Potential for shock from toaster.

NOT A LARGE HAZARD, ESTIMATE IS CONSERVATIVE:

- MULTI-FIBER FAILURE STATISTICS
- DISTRIBUTION OF USER RESISTANCE TO GROUND
- CURRENT CAPABILITY IS NOT LETHAL

Figure 22.- Shock hazard evaluation.

1. A DATA BASE HAS BEEN COLLECTED FOR USE IN RISK ANALYSIS ON THE VULNERABILITY OF ELECTRONIC, ELECTRICAL AND AVIONIC EQUIPMENT TO T-300 FIBERS.

2. FIRE-RELEASE EXPERIMENTS HAVE SHOWN THAT FIBER RESISTIVITY IS UNCHANGED AND DAMAGE POTENTIAL IS APPROXIMATELY THAT OF VIRGIN FIBER.

3. POST EXPOSURE AVIONICS VULNERABILITY HAS BEEN INVESTIGATED AND WILL BE USED IN THE RISK ANALYSIS.

4. THERE IS A NEGLIGIBLE SHOCK HAZARD FOR A SMALL NUMBER OF HOME APPLIANCES. THE HAZARD WILL BE OVER-ESTIMATED BY USING SINGLE FIBER DAMAGE MODELS.

Figure 23.- Conclusions.

LARGE-SCALE FIBER RELEASE AND EQUIPMENT EXPOSURE EXPERIMENTS

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The large-scale testing is a very recent part of the risk analysis program as far as getting the field work completed. The final test was performed less than one week ago and data from all of these tests is just beginning to be available. About a year ago at the last conference (reference 1) only very preliminary plans for this large-scale test program could be discussed, so a lot has happened in this past year which is the basis for this paper. The large-scale testing has been accomplished with two sets of tests as shown in figure 1. Outdoor tests have been run at the U.S. Army Dugway Proving Ground, Utah which were looking both for a better definition of the source, i.e., the amount of fiber released, in a full scale fire, and also its dissemination away from the fire. In the test planning using laboratory test results as a basis, the conclusion was reached that there was almost no chance of getting a sufficient level of exposure in downwind dissemination from any kind of large-scale outdoor test that could be performed within the limits of the national budget that would have any reasonable likelihood of failing electronic equipment. Therefore, a second set of tests were designed for equipment vulnerability to fire released fibers to be run in a shock tube at the U.S. Naval Surface Weapons Center, Dahlgren, Virginia. There was a possibility that some transfer function work also might be done in the shock tube, however, as the planning and preliminary testing progressed, the effort was concentrated on vulnerability entirely.

Dahlgren Shock Tube Tests

Figure 2 is an aerial photograph of the 0.8 km long shock tube which was modified near the mid-length to burn carbon fiber composites in a jet fuel fire. The fire-released fibers, combustion products and heated air were transported through the tube by exhaust fans installed in the large end. An exposure area for equipment vulnerability testing was developed near the large end so that reasonable mixing and cooling could occur in the air stream prior to passing by the equipment under test. A water curtain filtered the carbon fibers and much of the soot out of the air before it was exhausted out of the tube.

Fifty-four fire tests were run to develop and validate a technique for getting maximum dissemination of fire-released single fibers down to the equipment exposure area for the vulnerability testing. The technique which was developed included a rotating basket (figure 3) that was suspended in the fire in such a manner that the composite material in the basket was tumbled continuously throughout the duration of the fire. The composite material was cut into strips approximately 1 to 2 cm wide by 15 to 20 cm long which were delaminated to thicknesses of about four plies of composite prior to being placed in the basket. With this technique and burning and tumbling until no composite remained in the basket, a mass of single fibers equal to 0.5 percent of the initial fiber mass was released and transported to the exposure area. As a result, in test 53, fiber exposures were obtained which

were great enough to be capable of producing equipment failures.

Figure 4 lists the principal fire test parameters for test 53 in the shock tube. A half percent fiber release was obtained, but that was because the duration of the fire was about 200 minutes; the fire was burning in a 1.2 m square fire pan with commercial jet A fuel; temperatures were controlled around the specimen basket in the range of 950 to 1,000^{o} C. The shock tube tests were trying to simulate the fire parameters that Joe Mansfield had initially identified in the large-scale outdoor fire modelling that he was doing. The composite mass was totally consumed after 134 minutes of burning, much longer than the average aircraft accident fire. But this test was run that long in order to get the maximum dissemination of fibers down the tube. At the exposure area, the fibers were all carried by air being moved through the tube; the plume was constrained by the inside walls of the tube and could not expand the way it would normally. Measured air velocities were about 0.7 m/s. Air temperature moving past the equipment was about 30^{o} C - just about a five degree rise over ambient which was well within operational temperature limits for the equipment.

The amount of fibers being disseminated in this particular test was measured by various types of instrumentation (figure 5). Sticky papers were used both laid flat for fiber deposition and in the form of sticky cylinders which provide a measure of exposure. Fibers were collected with a Peterson aerodynamic sampler which will be discussed later in more detail in connection with the Dugway tests. The high voltage grid was described by Taback in the Equipment Vulnerability paper (ref. 2). A light-emitting detector (LED) was one of the instruments that was modified for use at Dugway from an earlier design used at China Lake last year (ref. 3). The modified design was operated in the shock tube for a check on its ability to sense fibers in a sooty atmosphere. Two NIOSH Millipore filters were injected into the airstream for short periods of time to sample that environment for the possibility of short fibers. A total of 228 instrumentation pieces were operated to detect carbon fibers.

Figure 6 presents some of the results from that instrumentation for the sticky papers. The buildup in fiber exposure as determined from the sticky cylinders is plotted as a function of composite burn time. Each set of cylinders was inserted in the tube for a 15 minute interval and then removed and a new set was inserted. Fibers collected on these cylinders gave an indication on an incremental basis of the buildup in fiber exposure with burn time that can be seen to be approximately linear up to a value of about 8 x 10^5 fiber-s/m^3. This is much greater than the exposure obtained from sampling by sticky cylinders that were in the entire time (continuous). This is an indication that the environment was probably saturating these continuous samplers and, therefore, a low count of exposure was obtained. The horizontal surface deposition stickies located on the floor of the tube indicated a much greater exposure at the end of the test than either form of sticky cylinder. This also would indicate a saturation of both forms of sticky cylinder instrumentation.

A similar plot of fiber exposure is shown in figure 7 for the high voltage grid, which because of its ability to sense fiber hits in real time is able to

provide a measure of exposure with time. Again a linear rate of fiber release is observed with the only difference from the previous data being exposures three times as great at the end of test as from any of the stickies. A verification of exposure from the high voltage grid is provided by the cumulative sample that was collected in the Peterson sampler and was not subject to saturation. A good correlation is shown at the 150 minute end point. Peak exposures on the order of 10^7 fiber-s/m^3 were determined at the end of the test.

Figure 8 shows the fiber length distribution that came out of this test. Fibers collected in the Peterson sampler were sized for length and the results are shown by the solid bars. Fibers were sized on the sticky papers and they're shown by the dashed bars. An exponential expression was fitted to this data and the agreement appears reasonable except at the short fiber lengths less than 1.5 mm where the sampler collection efficiency becomes poor. The average fiber length for fibers that are greater than one millimeter in length (the ones that are of interest for vulnerability) is two millimeters in this test.

Six Dynaco amplifiers were installed in the shock tube and exposed to the same environment as the various sampler instruments. Figure 9 is a plot of their failure occurrences with burn time. Four failed in the first ten minutes, then exposure continued for another fifteen minutes to about twenty-five minutes total before the next one failed and finally the last one failed at about forty minutes total exposure. The total composite burn time was on the order of 150 minutes so failures of these amplifiers occurred in less than half of the time required to get the composite completely disseminated. If the time axis is changed to fiber exposure using figure 7 data, and if the failure scale is non-dimensionalized in terms of probability of failure, the results are shown in figure 10. The experimental data, just like it was before but now in terms of fiber exposure, show all units fail in an exposure of slightly less than 4 X 10^6 fiber-s/m^3. These failure data can be fitted very nicely with a probability of failure calculation based on chamber test parameters as described in reference 2.

Dugway Outdoor Tests

Figure 11 presents the kinds of test parameters that were used in the design of the outdoor fire tests conducted at Dugway Proving Ground, Utah. The size and duration of the fire and the quantity of fuel burned, were basically sized by examining what seemed to be representative in commercial aircraft accidents of the fuel-fed fires occurring in this country over the last ten years (ref. 4). Forty-five kg or more of composite material was burned in each fire. This was made up of carbon-epoxy aircraft components that were supplied by the commercial aircraft manufacturers from test programs and also by two military aircraft companies. These are all components that are representative of the state of the art today in carbon-fiber-epoxy composite components. Several of them were actual flight components. The bulk of them, though, came out of technology test programs. The weather conditions specified were quite different for the two types of tests that were to be run. For one group called "source tests" the wind speed was essentially zero. A second group

which are called "dissemination tests" required winds that range upwards to about five meters per second or about ten miles an hour and a very restricted wind direction of 320 degrees plus or minus 35. There is a reasonable probability of waiting for up to a month to get this kind of a wind direction coupled with this kind of a wind velocity. This program was extremely fortunate in weather which permitted three tests in less than two weeks time.

A major consideration in the design of the outdoor tests was the kind of instrumentation that could be used at Dugway. One of the concerns was to be able to sample in the plume above the fire as many times and as independently as possible to obtain a good representation of what was being given off from burning the composite in the large outdoor fire. Figure 12 lists an overview of all of the instrumentation. The Peterson samplers were a development that came out of this program designed to sample close in to the fire, but still in the plume above it. They operated in an environment very close to the end of the visible flame in the plume. A vertical array of stainless steel mesh-covered cans was also fabricated. Both of these instruments were supported off towers that are close to the fire. Next was a separate system of six sampling types flown from a large net that was supported by balloons and which sampled the plume downwind from the fire. And, finally, there was the ground-supported instrumentation representing four types of instruments whose locations ranged all the way from 91 meters to 19,000 meters downwind from the fire. These were instruments that were basically mounted on posts about a half meter above the surface of the ground. The total amount of instrumentation involved is in excess of 2,000 instruments for each of these tests.

Figure 13 shows in detail the location of the tower-supported instrumentation. The test site development started by building two fire pools, 10.7 m in diameter. The first fire pool was in the center of the array for fires which would be burned for the source tests with zero wind where the plume would rise straight up. The second fire pool was on the upwind side of the array for dissemination fires where the wind was going to be blowing and disseminating fibers from the cloud in the design direction. Four towers 60 m high were erected from which a steel cable network was suspended. The array of 61 Peterson samplers were hung from the steel cables in a pattern designed to sample the fire plume. This array could be raised or lowered by winches at each of the towers so the samplers could be serviced, and so that it could be positioned just above the end of the visible flames for the particular test conditions. Between the two downwind towers there was a set of vertical array mesh can samplers that were designed to operate from ground level up to 53 m in the air. These provided another opportunity to intercept the plume as it was being bent over and leaving the location of the fire.

Figure 14 is a photograph of the canopy of Peterson samplers suspended from the four towers about 40 m above the ground level at sunrise on one of the particular test mornings. The vertical array is between the towers downwind in the right-hand side of the photograph. Figure 15 is a photograph of the Peterson sampler. It is a stainless steel welded cylindrical can. The air enters through the inlet at the bottom and the entrained fibers are collected on a stainless steel mesh cylinder inside of this outer case. The soot goes on through the mesh cylinder and is exhausted out the back such

that during the fire test a partial separation of soot from the fibers occurs making the fiber sample easier to count after the test is over. The inlet and exhaust openings are sized for the aerodynamic pressures such that isokinetic flow exists for the velocity range of the hot plume. The vertical array consists of 221 stainless steel mesh cans (figure 16) 9.5 cm in diameter that are mounted on a set of vertical cables that are strung from a catenary between the downwind towers and are used to sample in the plume. For stickiness, the mesh is coated with a high temperature vacuum grease.

Figure 17 is a schematic of the balloon-supported Jacob's ladder, which consists of a net that is 305 m wide and 305 m high. The entire system is constructed with Kevlar cables to minimize weight. The net is suspended from a catenary that in turn is suspended from two blimp-type balloons. These were operated by the Air Force Geophysics Lab who had a balloon crew at Dugway for the duration of this test program. This whole system is stabilized by a series of tether lines out to the sides, in front and rear. The design is based on concepts which have evolved from earlier tethered balloon operations (Reference 5). Distances are such that from one extreme side tether anchor to the corresponding side tether line anchor on the other side is over two km. It's roughly one km from the net to these forward stabilization tie down points. The Washington Monument is drawn in scale on figure 17 just to give a relative sense of the size of this sampling net. Also shown schematically is the kind of intercept area that a typical fire plume would have with that net. The net is anchored 150 m downwind from the fire pool. Depending on the way the wind blows, within the directional constraints, the plume might be over to one side or the other side or right down the middle. Also, depending on velocity, the plume might intercept up near the top, in the middle, or down near the ground.

Figure 18 is a photograph of the net up and flying with one of the balloons and a part of the supporting catenary. The photograph covers about one-quarter of the net, from one side to about the center line and down to about mid-height. What appear to be little white squares at the net intersections of the horizontal and vertical lines, are the mesh viewgraph samplers that are literally a piece of bridal veil mounted in a viewgraph frame that is tied to the net at each of these locations. The net line spacing creates about 15 m squares with a sampler in each corner. This photograph gives an indication of the immensity of the instrumentation problem. For servicing the instrumentation between tests, the balloons were pulled down by winching in the aft tethers and releasing the forward tethers allowing the net to be laid down on a table on the ground that was constructed at about head-height so that people could work in under the net adding, removing or servicing samplers after a test. For each test, the balloons were inflated and the whole net was raised to an operating position as shown, held into the wind by the forward tethers.

The kinds of instrumentation that were used on the net are shown in figure 19. Viewgraphs were located at every one of the 420 intersections on the net. Other types of instrumentation that were on the net were generally in the areas where the heavy black dots are shown. All of this instrumentation, of course, had to be sized to be minimum weight so that it would not pull the net down,

distort it, or pull the balloons and net down. Figure 20 is a photograph of a typical installation where four pieces of instrumentation are located at one particular intersection of a horizontal net line and a vertical net line. This assembly is shown while it's down on the table. From left-to-right are the mesh-covered can which was added to a number of intersections to calibrate the viewgraphs, the mesh-covered viewgraph, and the high voltage Schrader grid. A cardboard version of the Peterson sampler with tail fins attached to keep it pointed into the wind is hanging below the other instruments, but is suspended off to the side slightly when the net is up and flying.

Beyond the balloon supported net, down range on the ground are sampling lines that were put out on the Dugway range at the locations shown in figures 21 and 22. Figure 21 is the short range sampling location out to about 2,000 meters of downwind range. Sampling line identifications are given by the double letter designations. The fire pool and towers are shown approximately to the correct scale. The balloon-supported Jacob's ladder was anchored across the centerline at a location between lines AA and BB. The dashed lines indicate the plus or minus 35^{o} allowable variation in design wind direction which bound the extent of cross-range sampling. The locations of the long-range ground sampling are shown in figure 22. At 19,110 m the sampling line was near the reservation boundary and the sampling line was long enough that it had to be bent to run along the boundary rather than going outside of Dugway's boundary. Figure 23 is a photograph of some of this downwind, long-range sampling area. It's bleak, flat terrain in general. This was taken from a location about 8 km from the fire pool, up on the side of a mountain which parallels the west side of the sampling range. The mountains in the background are off at a distance from here of about 40 km.

Figure 24 shows the specimen support table over the 10.7 m diameter pool. There was 5 - 8 cm depth of water in the bottom of the pool and 12.7 cm depth of fuel was pumped in and floated on top of that. The array of specimens laid out on the table were numbered for identification. Most of them were placed on the downwind side of the table, however, a few were on the upwind side for reference purposes. Typically, 13 to 25 specimens of different aircraft components were placed on the table to be burned in the fire. Also, several of the Peterson samplers can be seen down on the ground attached to the cable array that had not been raised until after work was completed on specimen installation and thermocouple instrumentation on the table.

Figure 25 is a photograph of the start of the second dissemination fire. At ignition, six pyrotechnic flares are set off firing into the fuel in the pool, under the specimens on the table. The over-head Petersons have been raised to an elevation about 30 m above the ground. Figure 26 is the fire after about ten seconds of burning. The large black cloud starting to grow is an indication of a well-established fire with the plume rising, but also being bent over by the prevailing wind. The view was taken from a quartering, upwind position. Figures 27 - 29 are sequence photographs taken after one minute of burning, from a camera position that is perpendicular to the wind direction. Figure 27 is the fire and initial part of the plume with a well-established fire ball extending for several pool diameters. The effect of the wind in blowing the fire to one side of the pool is evident from the amount of the table that is

showing. Strips of material that were delaminating off the specimens as well as clumps and single fibers were being thrown out of the plume as it moves downwind. Swinging the camera around to the right, figure 28 is a photograph of the next part of the plume as it passes between the two downwind towers. Some of the vertical array can be seen in front of the plume, but imaged against the dark background. Some of the Peterson samplers on the near side of the plume also are imaged against it. The plume passes generally through the towers, actually splitting itself on this one tower at this particular time. Figure 29 was taken swinging the camera still farther to the right with the end of the plume penetrating through the viewgraph samplers that were mounted on the Jacob's ladder net supported from the balloons. The net cables are not visible in this picture and the balloons are well above the top of the picture. But this gives a view of the adequacy of the instrumentation intercepting the plume.

The next sequence of photographs (figures 30 - 32) was taken from a location about 5 km to the side and 2 km downwind from the fire site after about 10 minutes of burning. Figure 30 shows the plume building up and passing through, but well beneath the two balloons supporting the Jacob's ladder. Swinging the camera around to track the full length of the plume down range in figures 31 and 32, the plume remains essentially at constant height against an inversion, but is approximately 6 km long. The end of the plume terminates just beyond figure 32. The mountain in the background is 12 km away.

Figure 33 shows typical residual material that was left on the rack after the 20-minute fire test. This is residual material from the third dissemination fire. It was two horizontal components and the vertical component of a tail from an F-16 fighter aircraft, which were burned in a fire identical to the second fire. In this fire, however, the steel table that was supporting the specimen collapsed after 5 minutes of burning. Nevertheless, the components stayed in the fire and show evidence of being well torn up, delaminated, and burned.

The other type of fire, a source fire, with essentially a zero wind condition is shown in the next sequence of photographs. Figure 34 was taken at ignition. The specimen table has been re-built from the last fire and is over the other fire pool. As the fire starts, figure 35 shows it at 6 seconds; figure 36 shows it at 30 seconds; and figure 37 shows it at one minute. Development of the plume going essentially straight up and being sampled entirely in the overhead Peterson canopy can be clearly seen as time advances. Another series of photographs that was taken from a helicopter of this same fire are shown in figures 38 - 43. The helicopter was flying in the vicinity of the fire throughout the time, but generally circling around the plume so in some of these pictures the cloud pattern or the shadow on the ground will change positions depending on the location of the helicopter. And as time continues on, the plume rises up to the inversion layer, flattens out, and then drifts slowly in the direction of the prevailing low velocity wind. Ground observers stated that the cloud persisted in the general area for times up to four hours after the fire.

Figure 44 is a summary of the meteorological conditions in each of these five tests. The three with dissemination had wind speeds on the order of five

meters per second. The significant thing here is that the wind direction was essentially on the two limits on the first two tests, but on the third test the wind was close to the design wind direction of 320 degrees. Weather stability condition was neutral on these dissemination tests. It was stable on the last two source tests where there was essentially no wind velocity and variable direction.

One obvious outcome of the three dissemination tests was the strips of material that delaminated and were carried downwind for a short distance before they fell out of the plume and deposited on the ground (figure 45). These were picked up on sweeps out over the ground area that defined the magnitude of the density of the strips and the quantity of material that was picked up. The first test was off to the west, the second test was off to the east, and the third test right down the center line. The third test deposited material a bit farther downwind than the first two. The location of the Jacob's ladder net at about 120 m downwind from the fire pool made it necessary for strips to pass through the sampling net to get to the indicated areas on the ground. Figure 46 is a photograph of one of the viewgraphs on the sampling net that indicates that it intercepted two of these strips. There are also a large number of single fibers on the viewgraph but they don't show up at this magnification.

The high voltage Schrader grids flown on the net gave an indication of the rate at which fibers were being deposited on the samplers on the Jacob's ladder. Figure 47 shows the fiber deposition for one particular net intersection about in the middle of the plume on the third dissemination fire test. Although the rate is not linear, it does indicate a continuous flow of fibers during the burn after the initial 2 - 3 minutes from ignition. The maximum deposition is on the order of about 2 X 10^4 fibers per square meter.

Figure 48 is a tabulation of an estimate by the Dugway data analysis group on the single fibers that were released in each of the tests. Note that the total number of fibers released in each of these tests was on the order of 10^8. There were variations from individual test to individual test, but not significantly different. The amount of carbon fiber mass in the fire was essentially the same except for test D-3 which was the F-16 composite tail, and weighed about 60 percent more than the carbon fiber components in the rest of the tests. That fewer total single fibers came out of this test may have been due to the larger, heavier four pieces of composite or to the change in location within the fire when the table collapsed. But even with these differences the percent of single fibers released is all within a factor of three. Note that the average length of released fiber was as high as five millimeters. The last test was run only last week and not all of the results are available for it. The maximum release for these tests was 0.13 percent.

Figure 49 provides a "quick-look" at what was intercepted on the Jacob's ladder sampling net from initial readings of the viewgraphs. The outline in the upper left of the figure is the intercept of the cloud or the soot outline on the net as it was picked off from the various viewgraphs. The symbols indicate areas in which clumps were found, and they're pretty well distributed over the whole cross section of the plume. Viewgraphs were read along two

cuts through the plume to get a quick look at the data. A vertical cut roughly through the middle of the plume showed the distribution of fibers indicated in the upper right of the figure. There seem to be several peaks vertically on fiber deposition, but peak values are on the order of 10^4 fibers per square meter. A horizontal cut also taken near the center of the plume is shown in the lower left. Again the peak value is about 2 X 10^4 which is not too much different from what was shown on the high voltage grid, (figure 47).

Finally, figure 50 lists the peak exposure levels measured from the downwind deposition of fibers on ground-based samplers for distances to 19,000 meters. These are the maximum exposure levels that were detected on those various cross range sampling lines from each of the first three dissemination trials. Close to the fire, the maximum exposure values are on the order of 10^3 fiber-s/m^3, but at greater downwind distances the exposures are almost at the point of being insignificant, but still are statistically sampleable on this system. These measured peak exposures also agree reasonably with predicted values from reference 6.

Concluding Remarks

Figure 51 summarizes the conclusions drawn from the large-scale fire-released fiber tests. They are considered to be tentative because much of the data are preliminary at this time due to the recent performance of the outdoor tests.

The greatest fiber release observed was the one-half percent in the Dahlgren Shock Tube where the composite was burned with a continuous agitation to total consumption. In the large-scale, outdoor fires at Dugway Proving Ground the greatest fiber release was 0.13 percent. Therefore, the one percent release that has been used in the risk calculations appears to be conservative.

Fiber length averages are based on measured lengths of those fibers that are greater than one millimeter in length. In the shock tube with the forced agitation the average length was two millimeters. Outdoors, the largest average length obtained for any one test was five millimeters. These two values bracket the three millimeter length used in the risk calculations.

Equipment vulnerability to fire-released carbon fibers was nearly identical to vulnerability in chamber tests which justifies the use of the carbon fiber chamber test data in the risk calculations.

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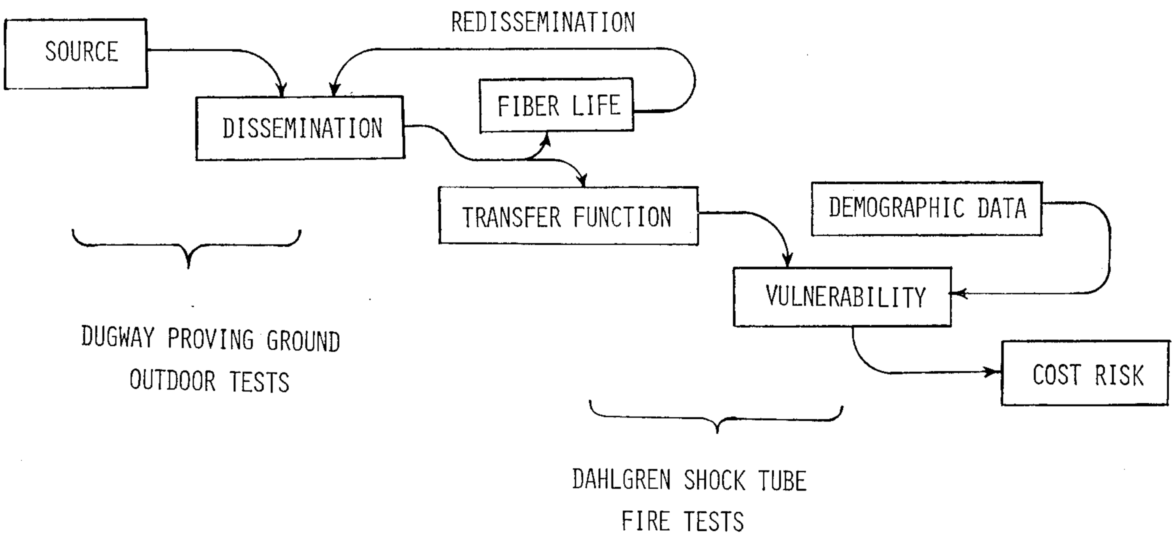

Figure 1.- Risk analysis elements.

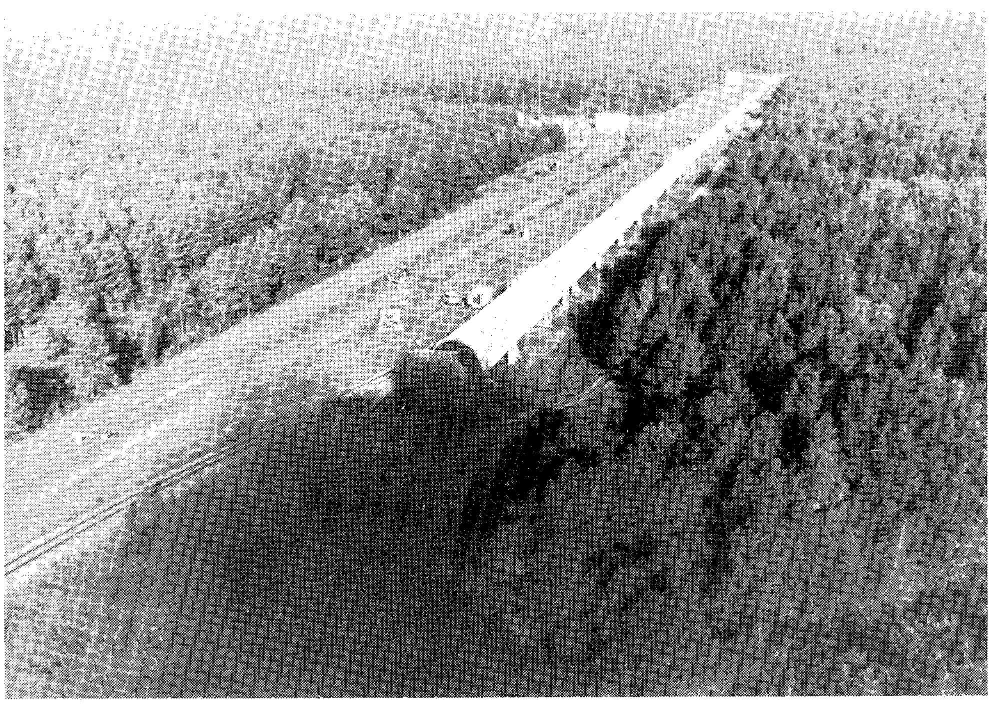

Figure 2.- Dahlgren "shock tube" burn test.

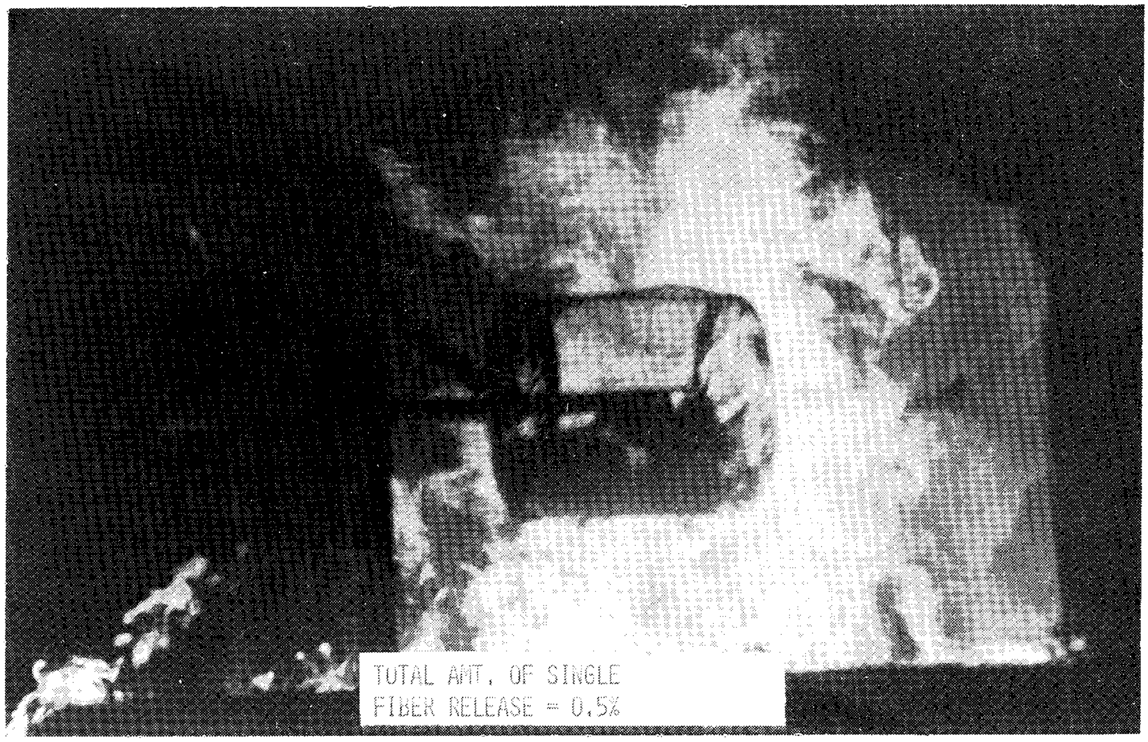

Figure 3.- Rotisserie agitation of carbon composites.

- FIRE

SIZE	1.2 m SQUARE (4 FT.)
DURATION	206 MIN.
FUEL	0.371 m^3 (98.1 GAL.) COMMERCIAL JET A
FLAME TEMPERATURE	950-1000^oC (1740-1830^oF)

- COMPOSITE

INITIAL MASS	9.988 kg
BURN TIME	134 MIN.
RESIDUAL MASS RECOVERED	3.361 kg

- EXPOSURE TABLE

AIR FLOW	18.9 m^3/s (40,000 CFM)
AIR VELOCITY	0.67 m/s (1.5 MPH)
AMBIENT TEMPERATURE	25^oC (77^oF)
TEST TEMPERATURE	30^o (86^oF)

Figure 4.- Dahlgren shock tube fire test parameters, test 53.

STICKY PAPER DEPOSITION	48
STICKY CYLINDER CONTINUOUS SAMPLING	95
STICKY CYLINDER INCREMENTAL TIME SAMPLING	75
PETERSON SAMPLER	6
SCHRADER HIGH VOLTAGE GRID	1
LED	1
NIOSH MILLIPORE FILTER	2
	228

Figure 5.- Fiber sampling instrumentation for Dahlgren shock tube fire test 53.

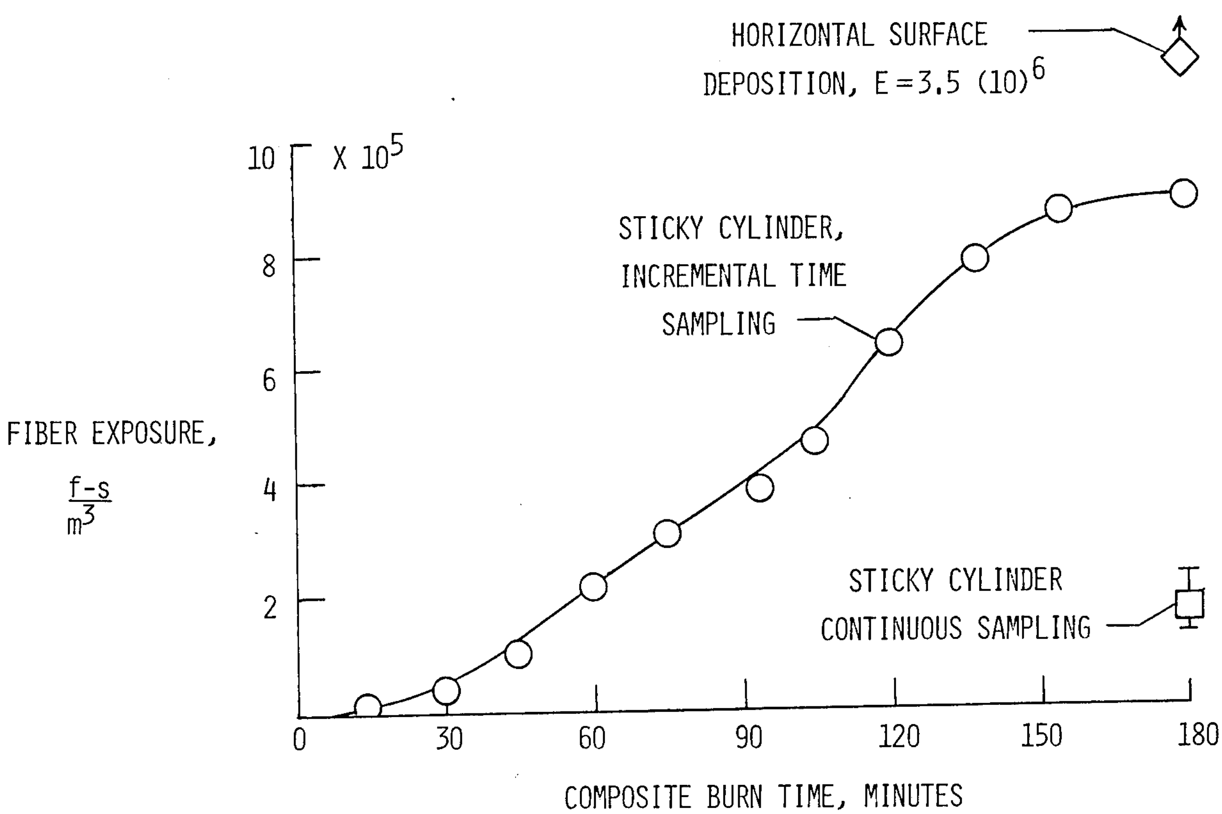

Figure 6.- Carbon fiber exposures measured by sticky paper samplers for Dahlgren shock tube fire test 53.

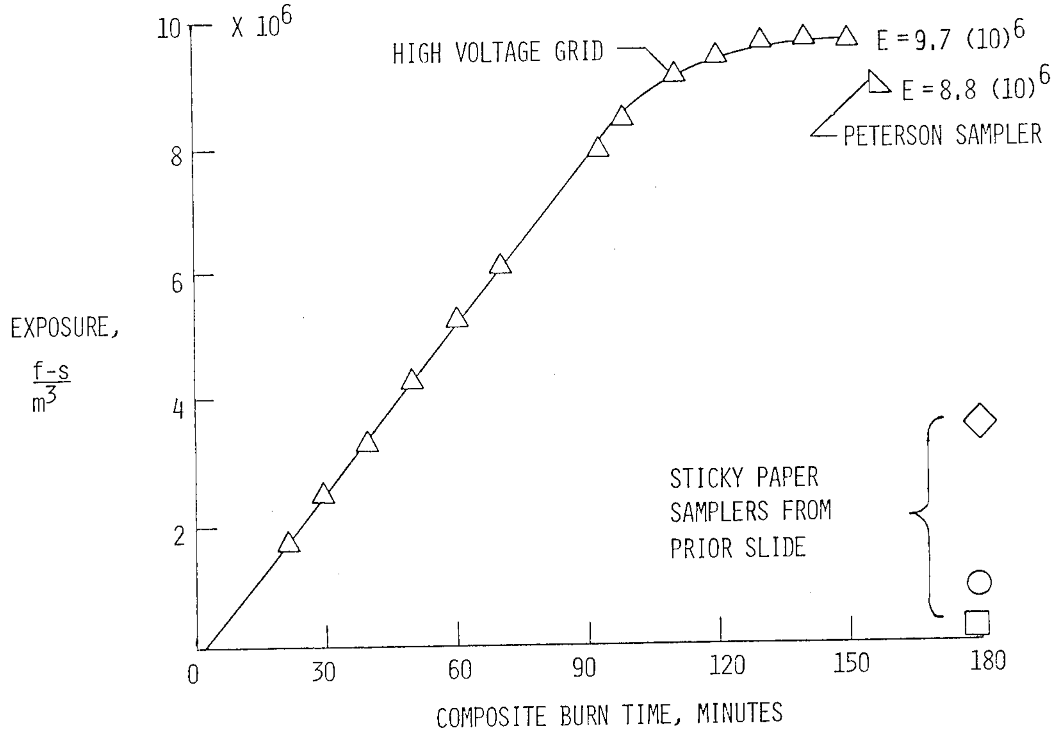

Figure 7.- Carbon fiber exposures determined by all instrumentation for Dahlgren shock tube test 53.

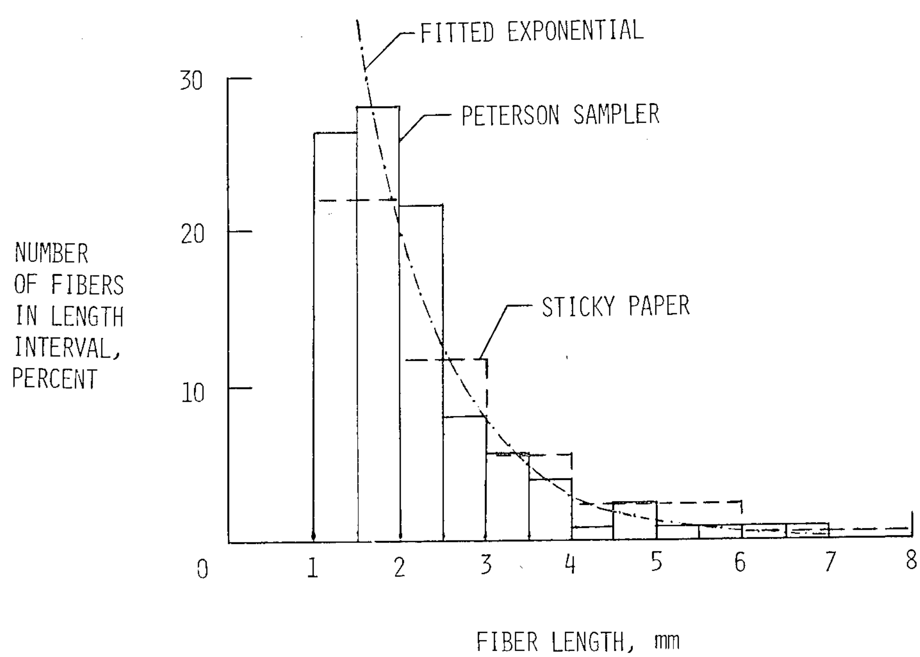

Figure 8.- Fire-released carbon fiber length distribution for Dahlgren shock tube fire test 53.

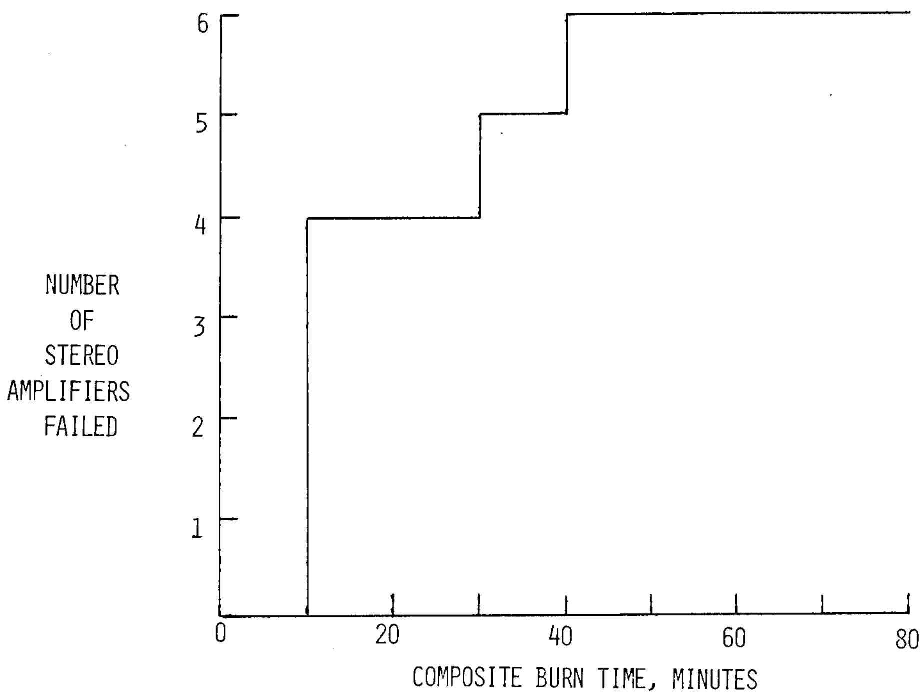

Figure 9.- Electronic equipment failures for Dahlgren shock tube fire test 53.

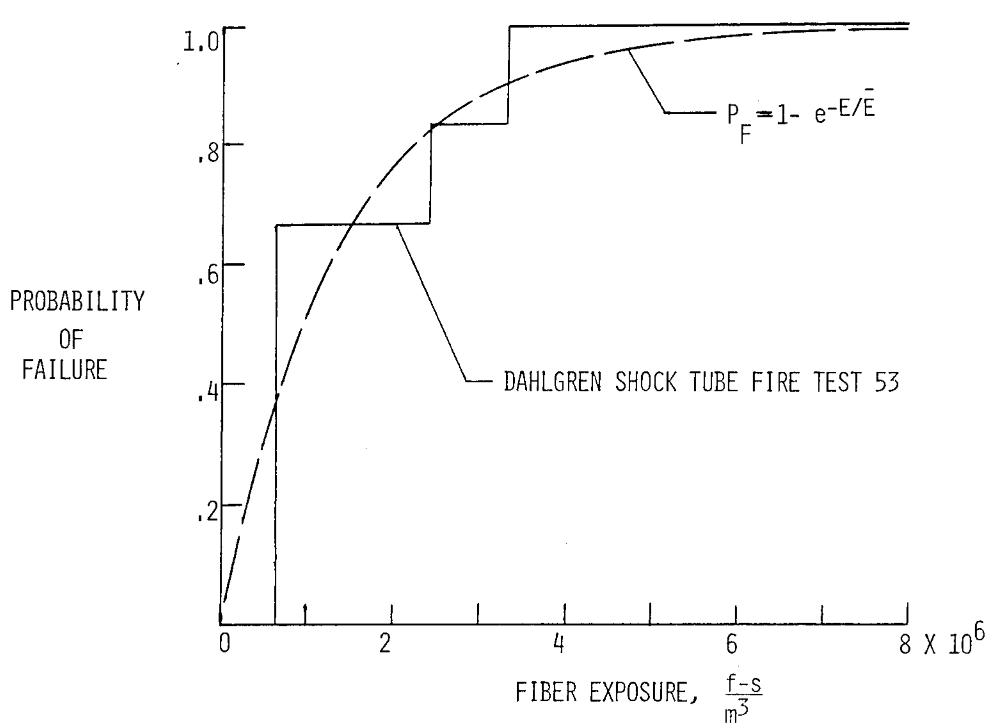

Figure 10.- Probability of electronic equipment failures from exposure to fire-released carbon fibers and to virgin carbon fibers.

FIRE		
	SIZE	10.7 m DIAMETER (35 FT.)
	DURATION	20 MINUTES
	FUEL	11.36 m^3 (3000 GAL.) JP-4
COMPOSITE	45 kg (100 LB.)	CARBON-EPOXY AIRCRAFT COMPONENTS
WEATHER		
	SOURCE TESTS	WIND SPEED 0-0.4 m/s
	DISSEMINATION TESTS	WIND SPEED 2.7-5.4 m/s
		WIND DIRECTION $320^0 \pm 35^0$

Figure 11.- Outdoor fire test parameters at Dugway Proving Ground.

TOWER SUPPORTED:		
PETERSON SAMPLER, OVERHEAD	61	
VERTICAL ARRAY MESH CAN	221	
		282
BALLOON-SUPPORTED JACOB'S LADDER:		
MESH VU-GRAPH	420	
MESH CAN	95	
CARDBOARD PETERSON	30	
NIOSH MILLIPORE FILTER	10	
LED	2	
SCHRADER HIGH VOLTAGE GRID	8	
		565
GROUND SUPPORTED, 91 m - 19,100 m DOWNWIND		
MESH CAN	833	
STICKY PAPER	464	
TIME CONCENTRATION	10	
ROTO-ROD	15	
		1322

Figure 12.- Fiber sampling instrumentation for outdoor fire tests at Dugway Proving Ground.

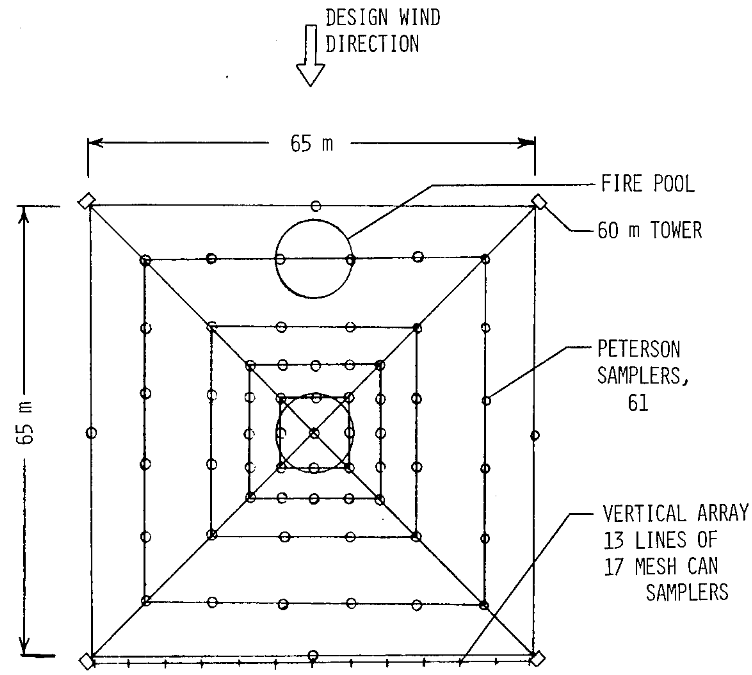

Figure 13.- Test-site layout for outdoor fire test at Dugway Proving Ground.

Figure 14.- Overhead Peterson sampler array suspended from towers at Dugway Proving Ground.

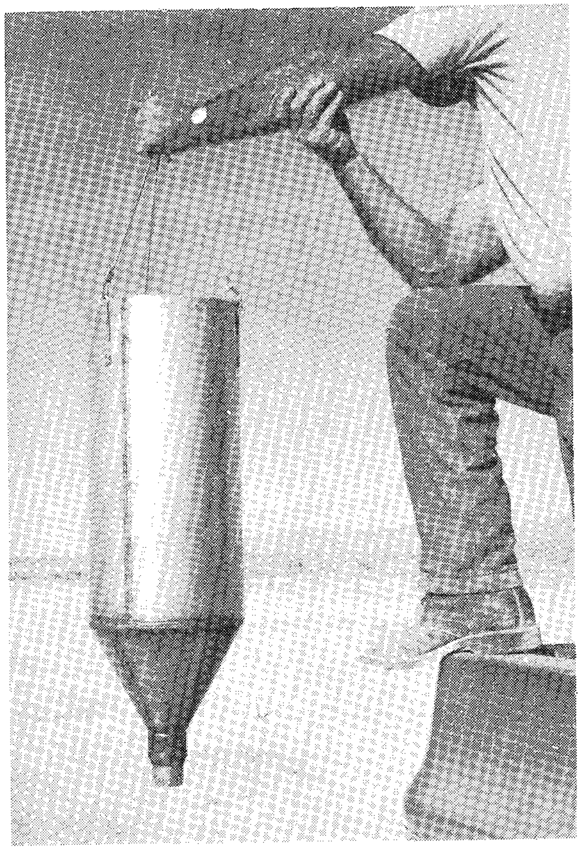

Figure 15.- Peterson sampler.

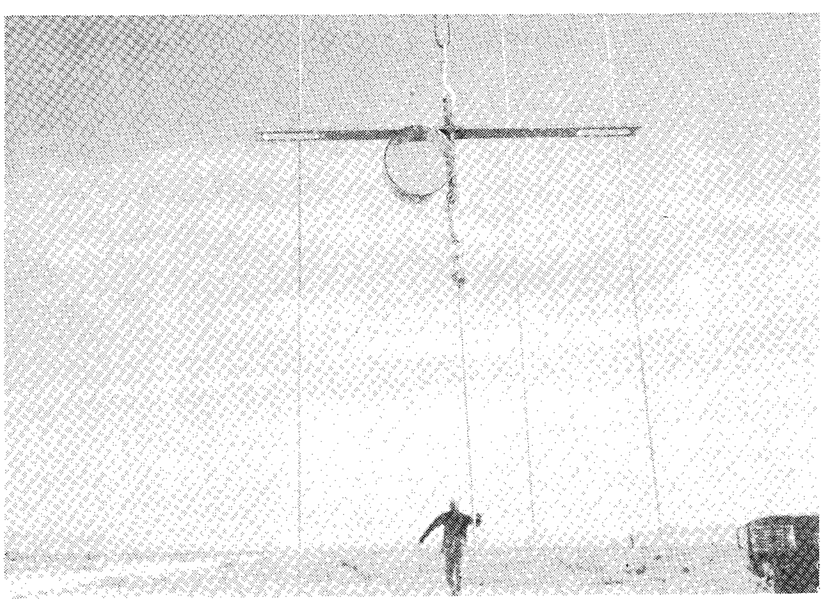

Figure 16.- Stainless steel mesh can - sampler on vertical array.

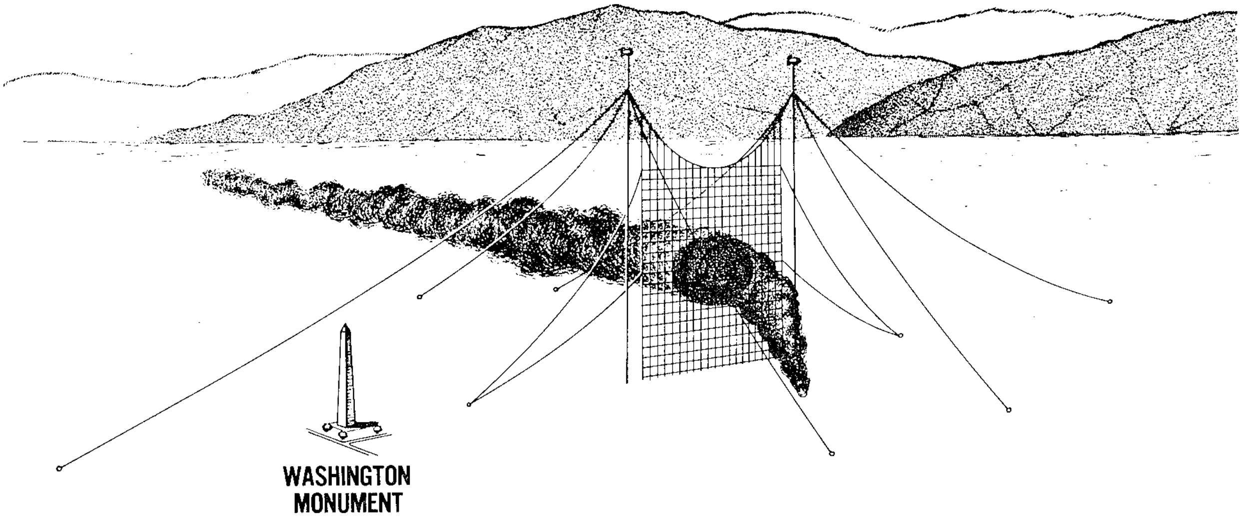

Figure 17.- Balloon-supported Jacob's ladder fire plume sampling net.

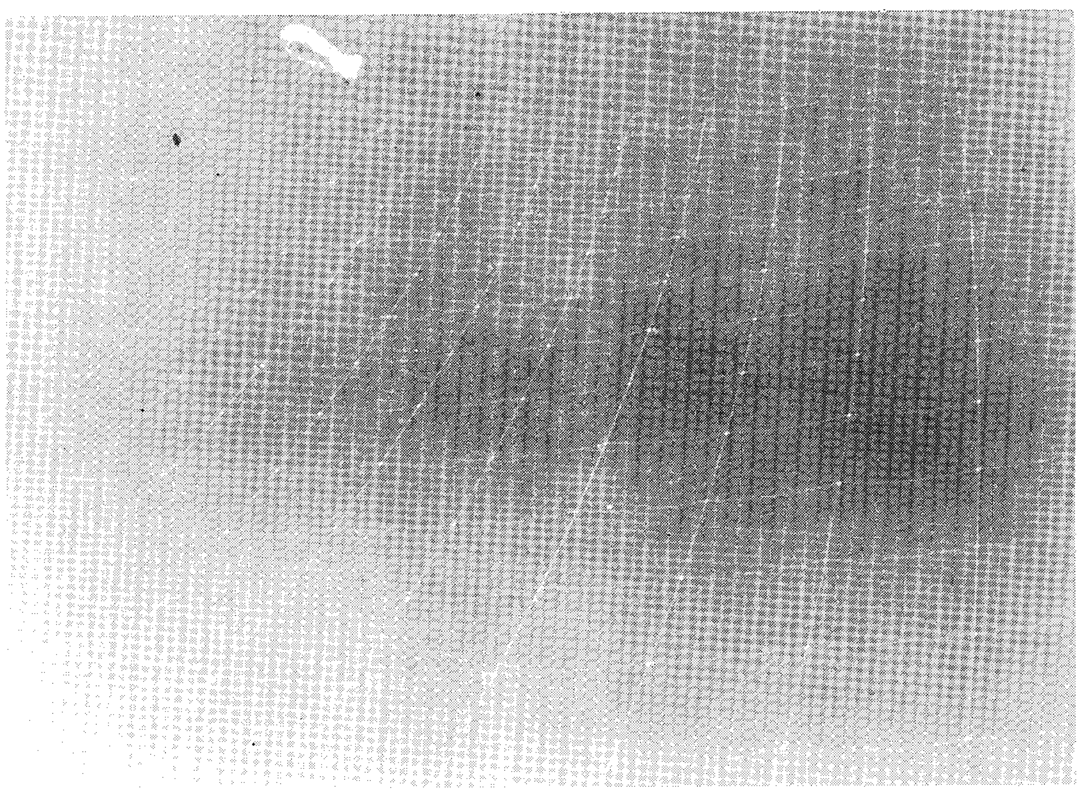

Figure 18.- Balloon-supported Jacob's ladder sampling net.

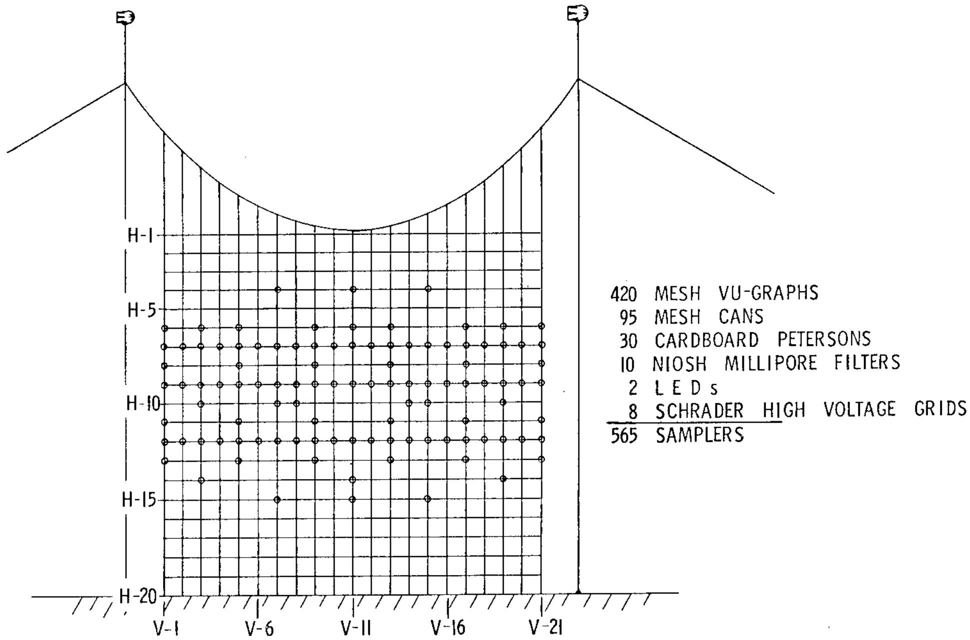

Figure 19.- Instrumentation on Jacob's ladder fire plume sampling net.

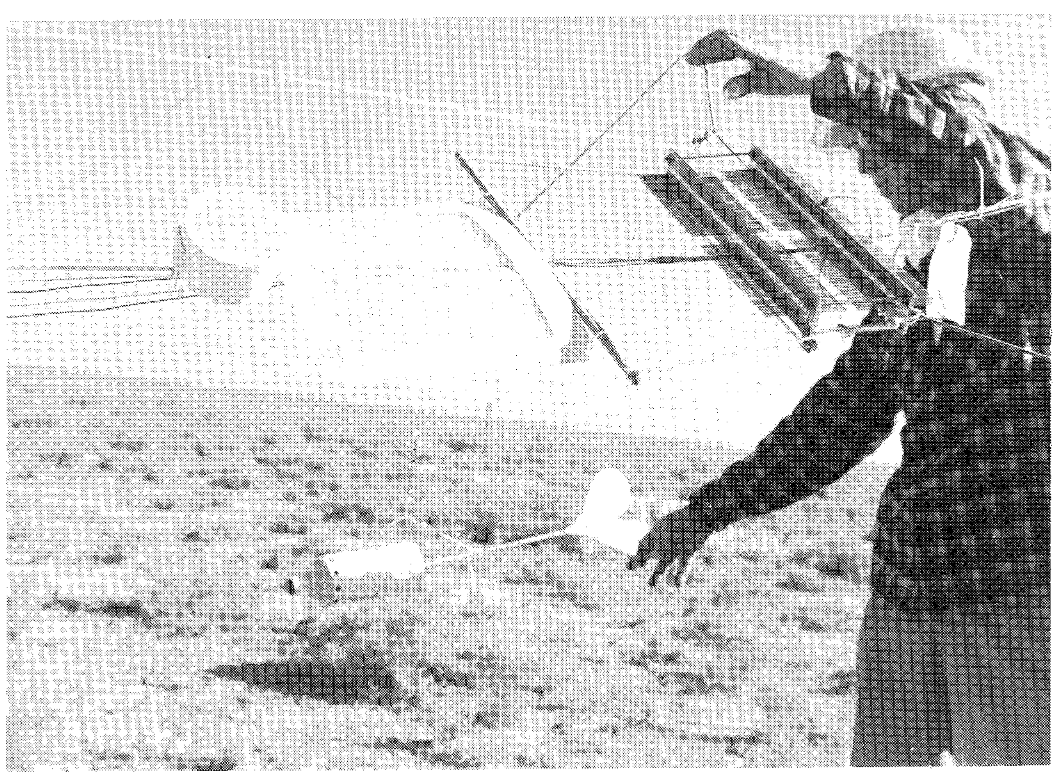

Figure 20.- Instrumentation on Jacob's ladder.

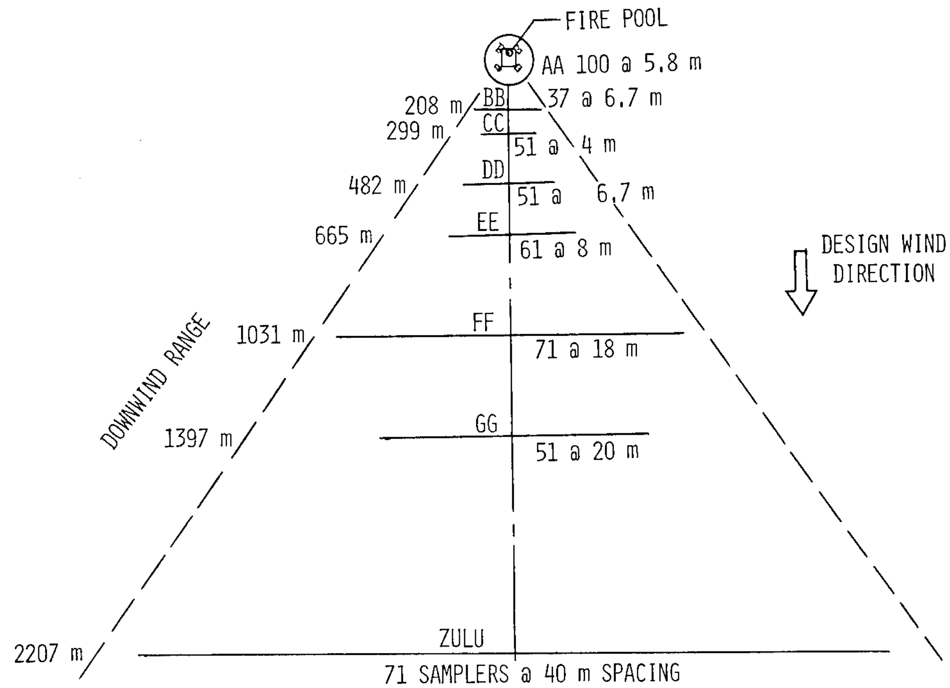

Figure 21.- Short range ground-supported fiber sampling lines at Dugway Proving Ground.

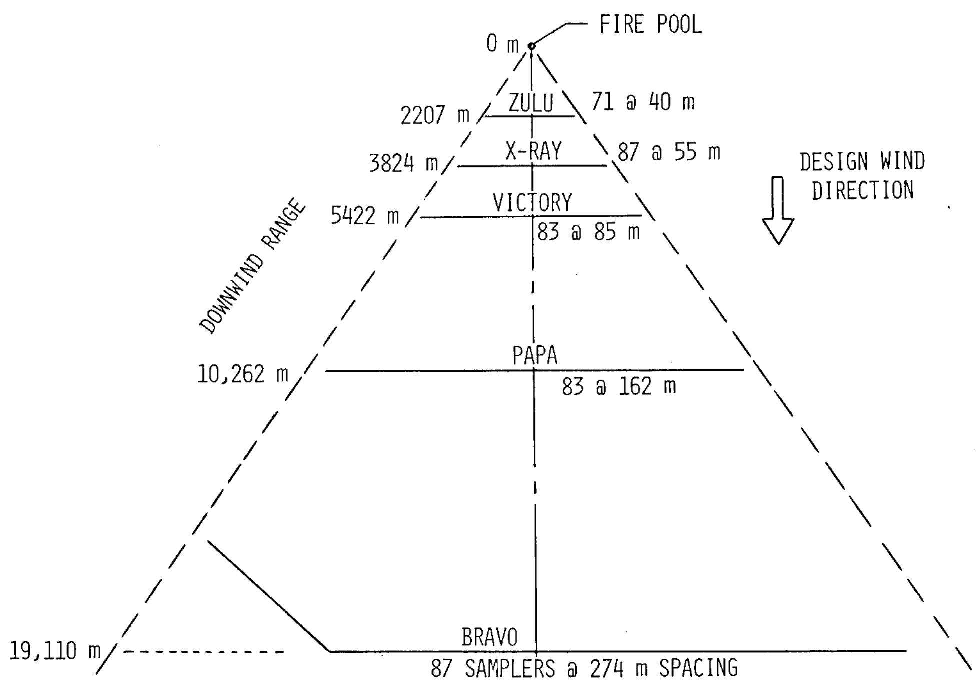

Figure 22.- Long range ground-supported fiber sampling lines at Dugway Proving Ground.

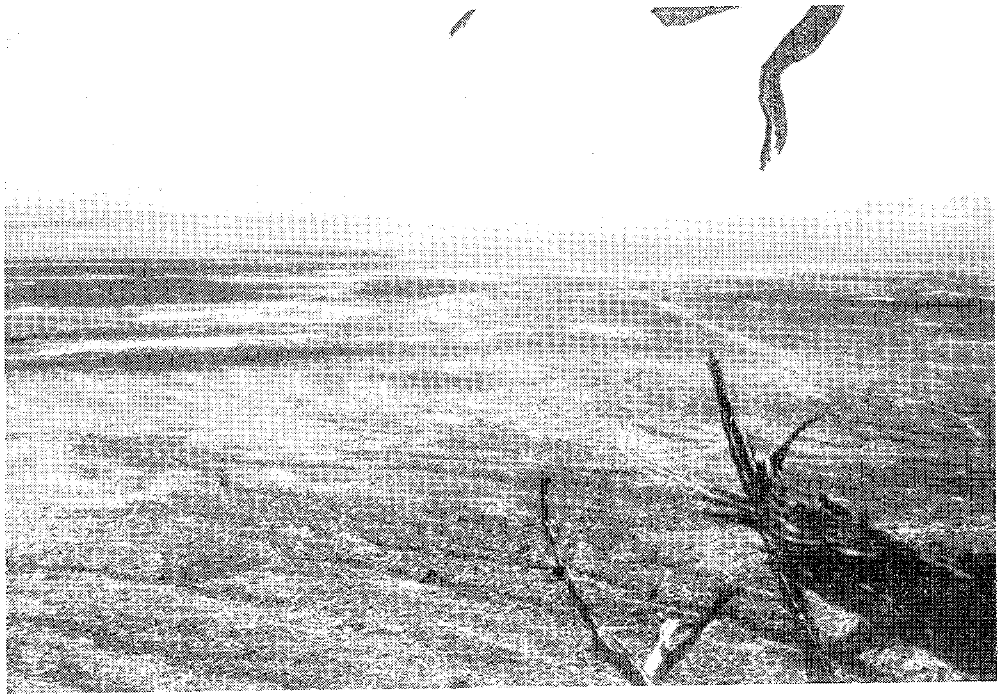

Figure 23.- Downwind, long-range sampling terrain.

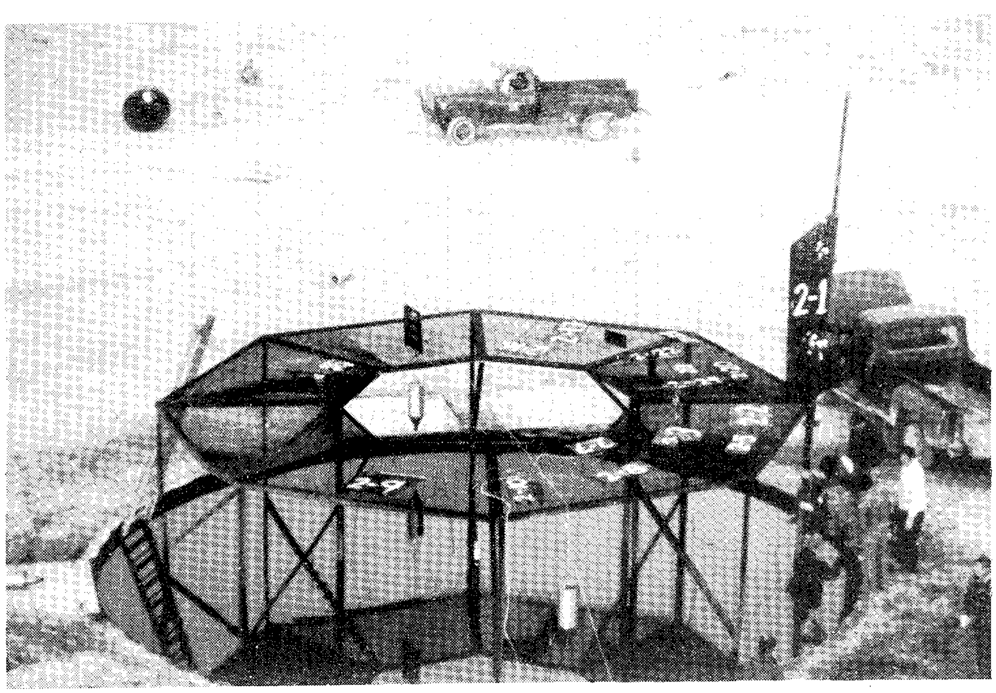

Figure 24.- Specimen support table over fire pool.

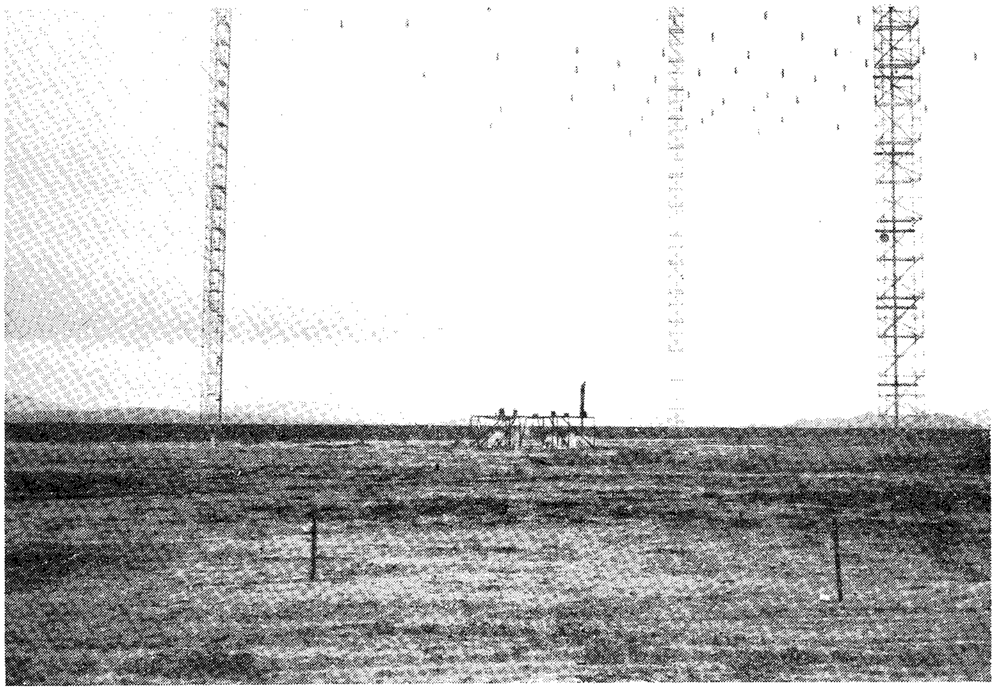

Figure 25.- Ignition of jet fuel in fire pool at start of second dissemination test.

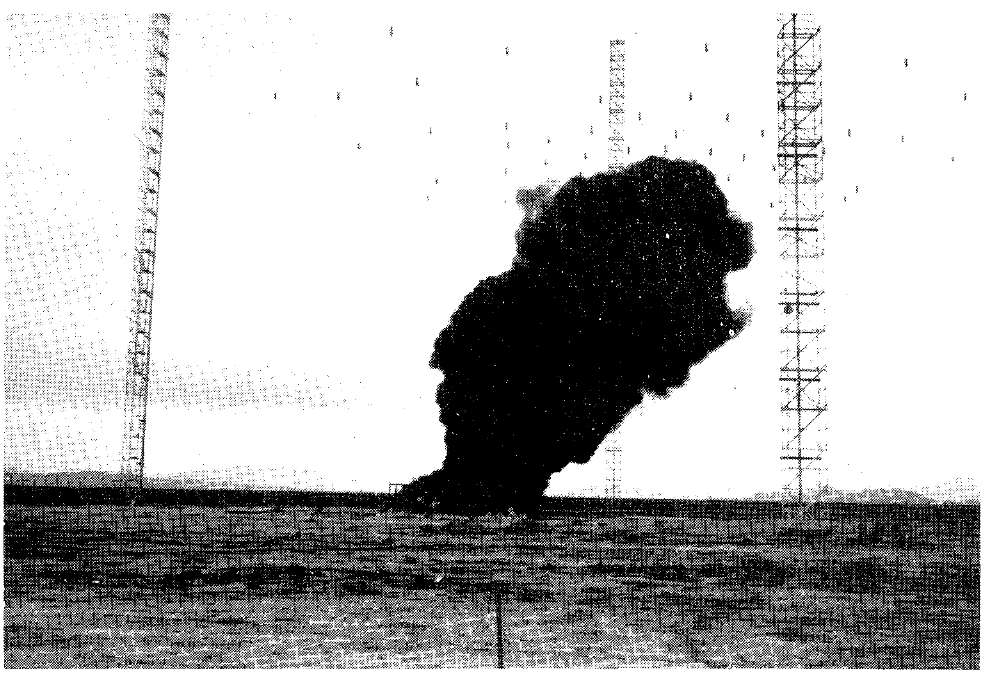

Figure 26.- Ten seconds after ignition of dissemination fire test, D-2.

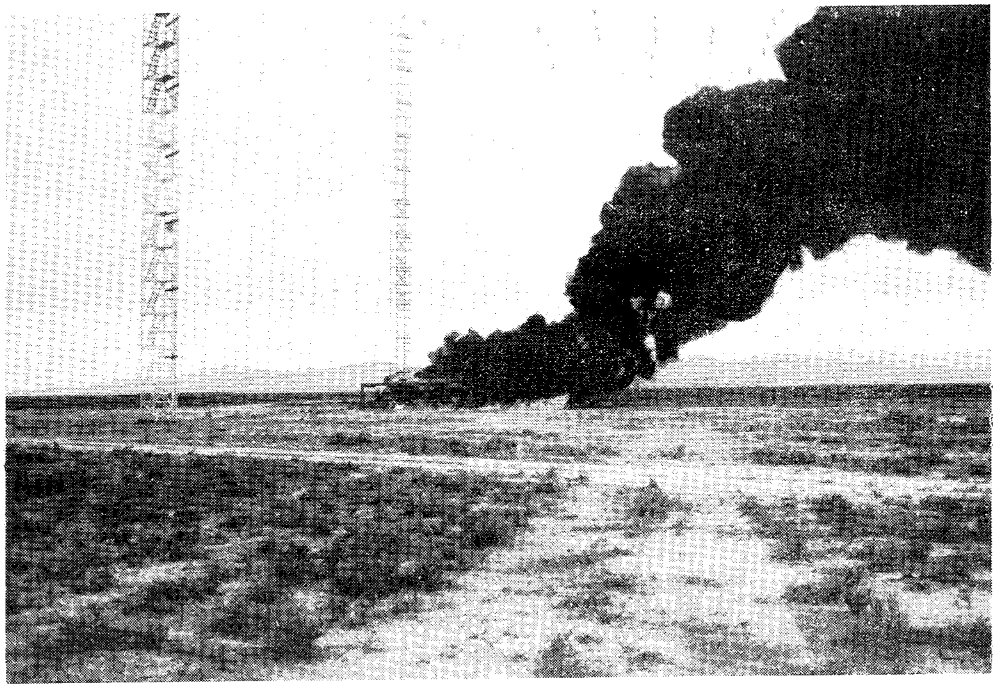

Figure 27.- Initial part of fire plume one minute after ignition, test D-2.

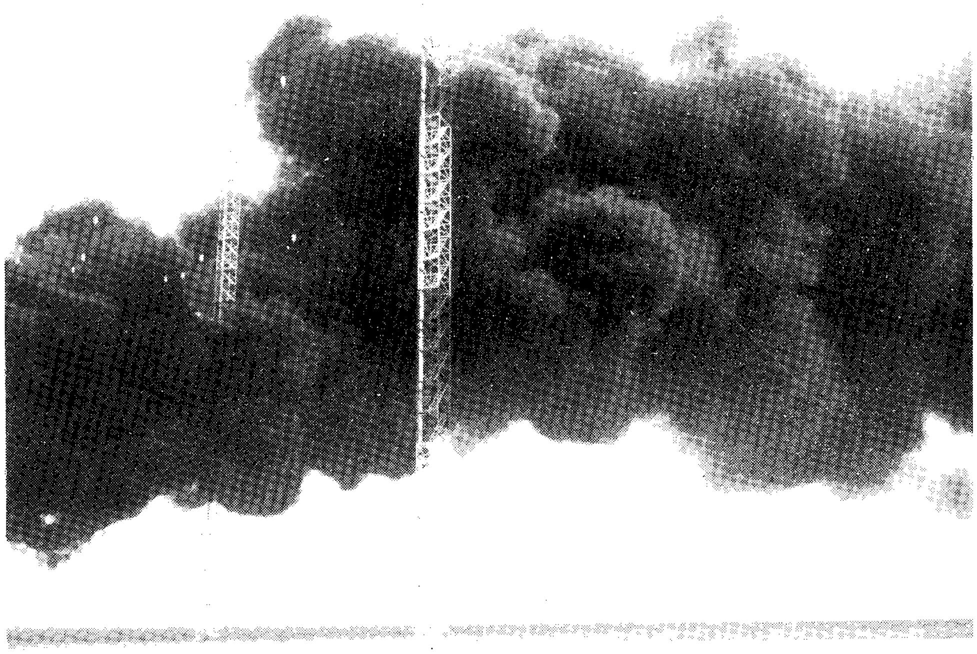

Figure 28.- Part of fire plume passing between two downwind towers, one minute after ignition, test D-2.

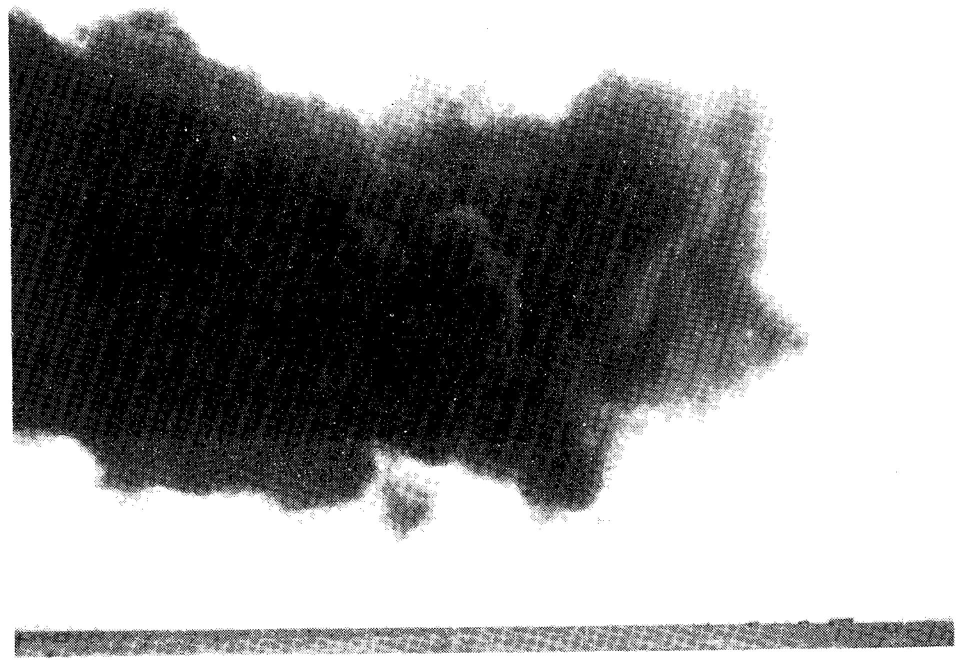

Figure 29.- End of fire plume, one minute after ignition, test D-2.

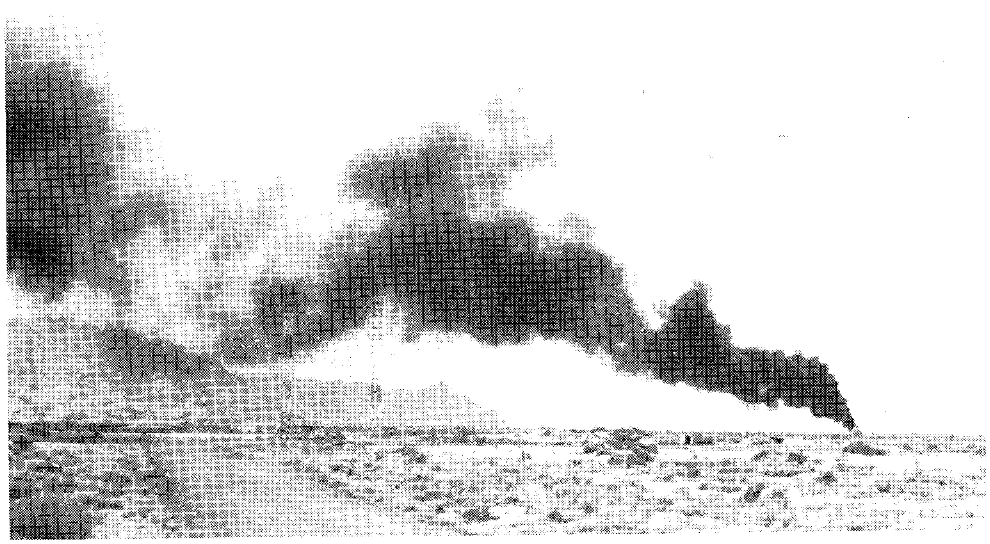

Figure 30.- Initial part of 6 km long plume, 10 minutes after ignition, test D-2.

Figure 31.- Middle part of 6 km long plume, 10 minutes after ignition, test D-2.

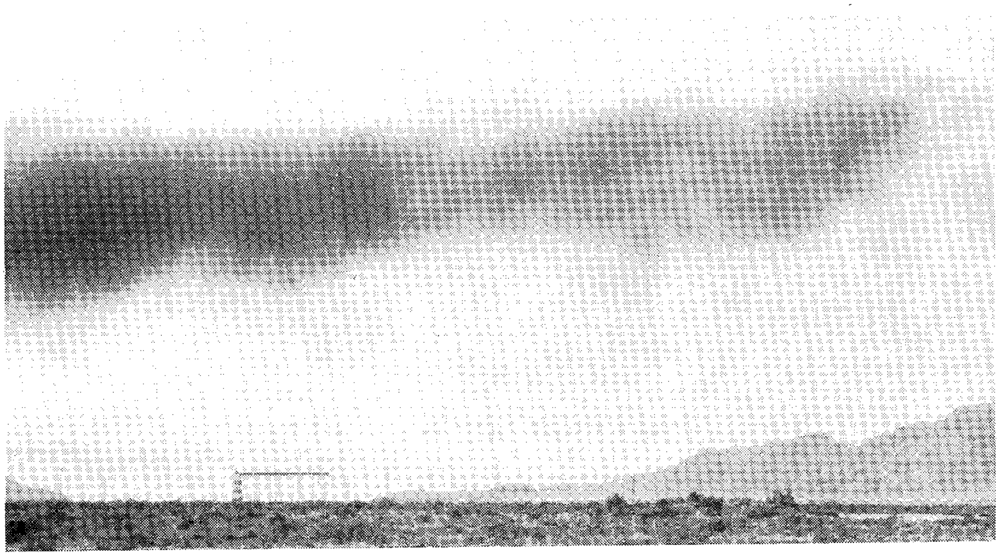

Figure 32.- Near end of 6 km long plume, 10 minutes after ignition, test D-2.

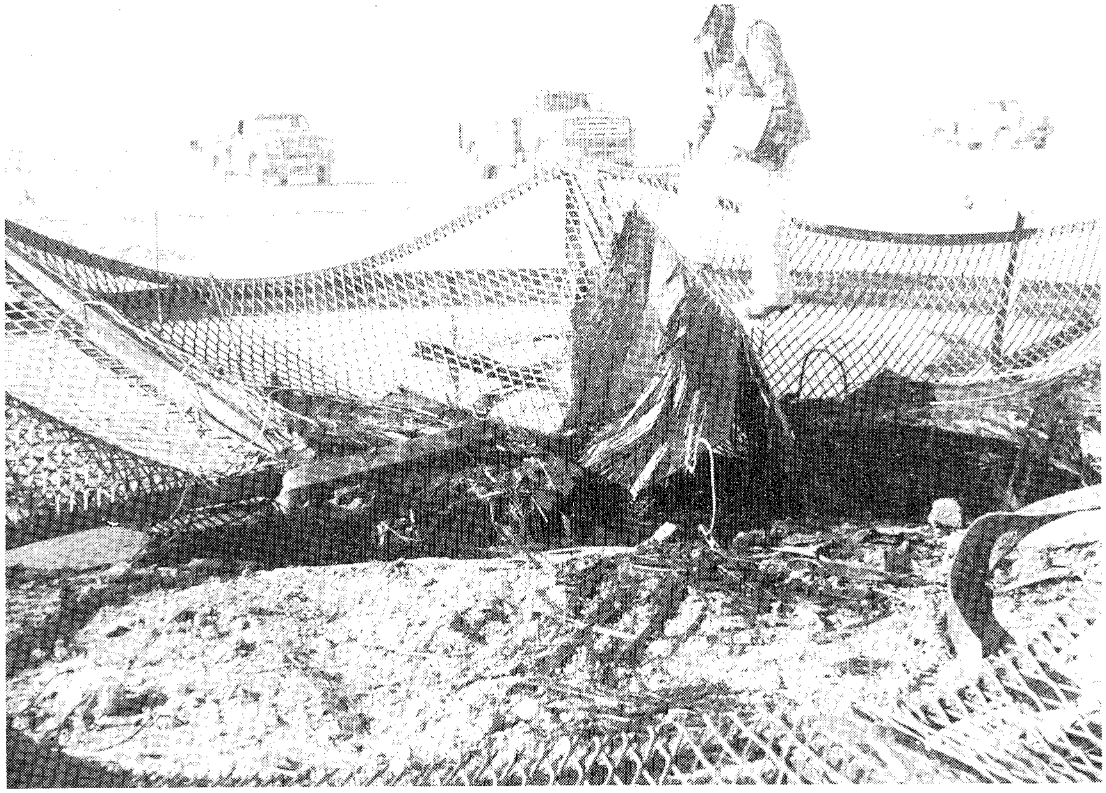

Figure 33.- Residual material after 20-minute burn of F-16 carbon fiber-epoxy tail at Dugway Proving Ground, test D-3.

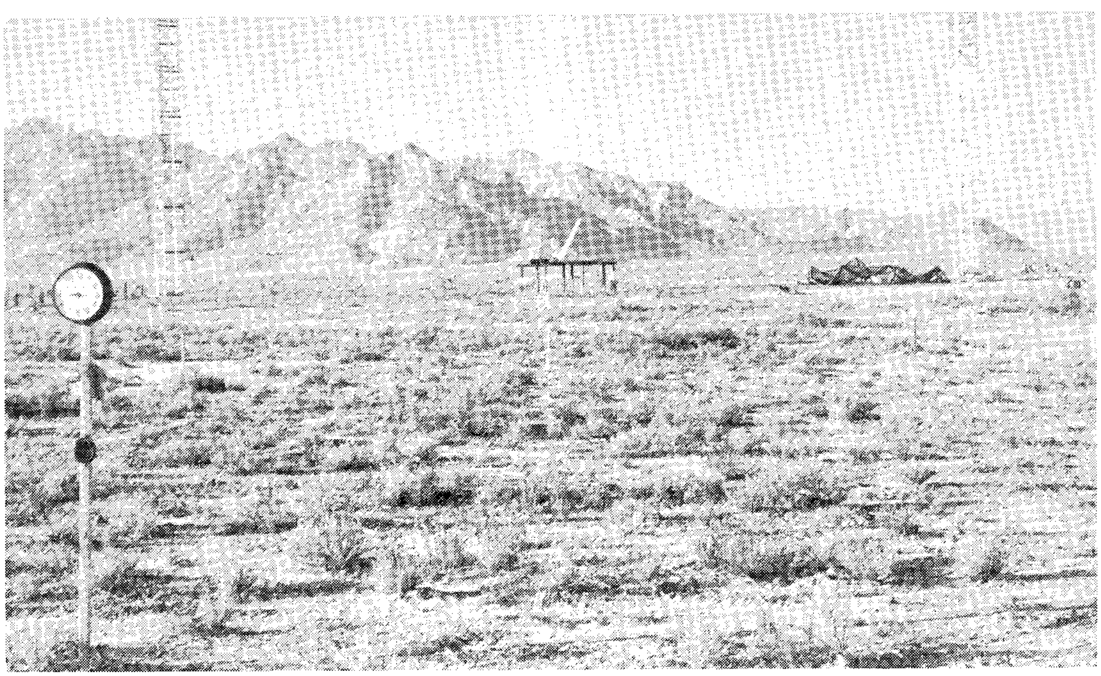

Figure 34.- Composite specimens on rack over 11-meter pool fire for test S-1 - ignition.

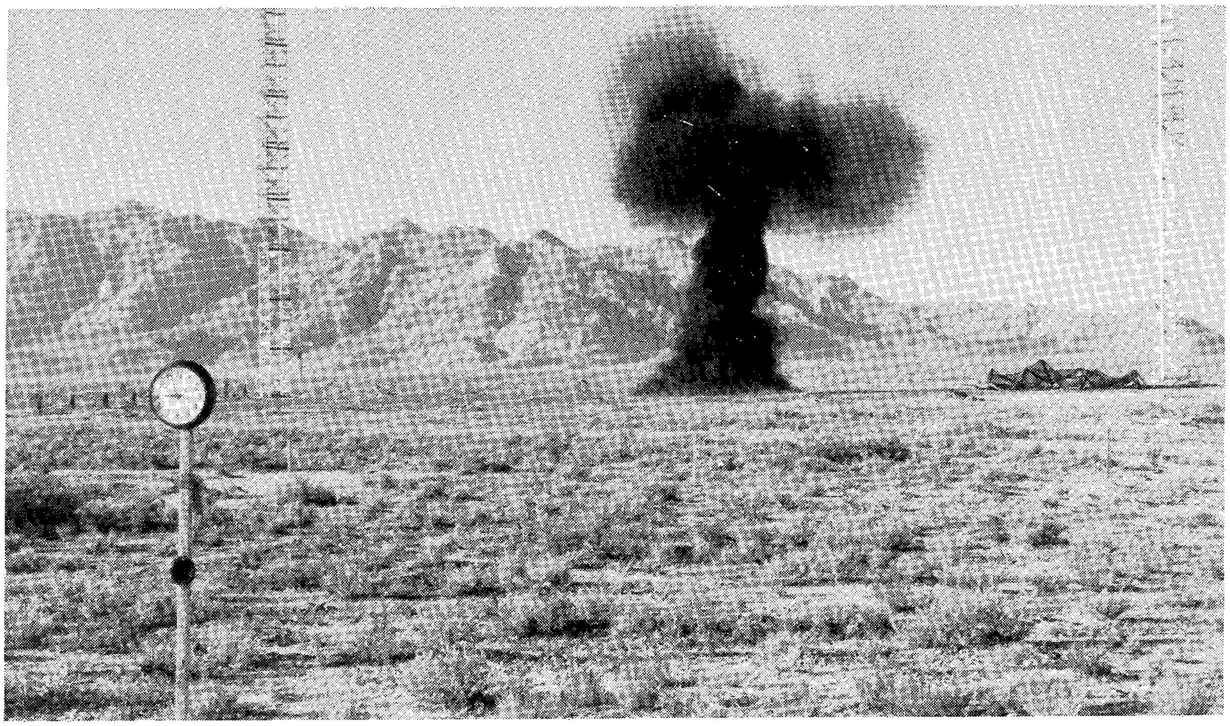

Figure 35.- 11-meter pool fire test S-1 - 6 seconds.

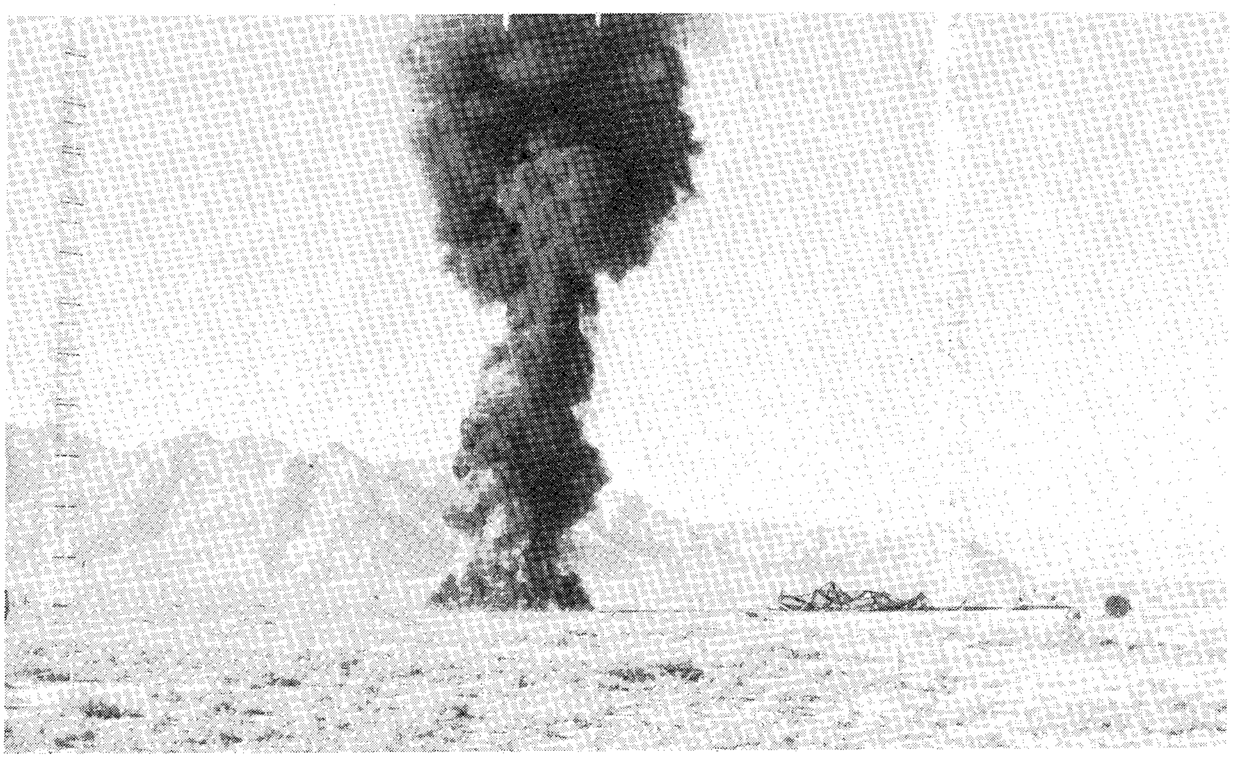

Figure 36.- 11-meter pool fire test S-1 - 30 seconds.

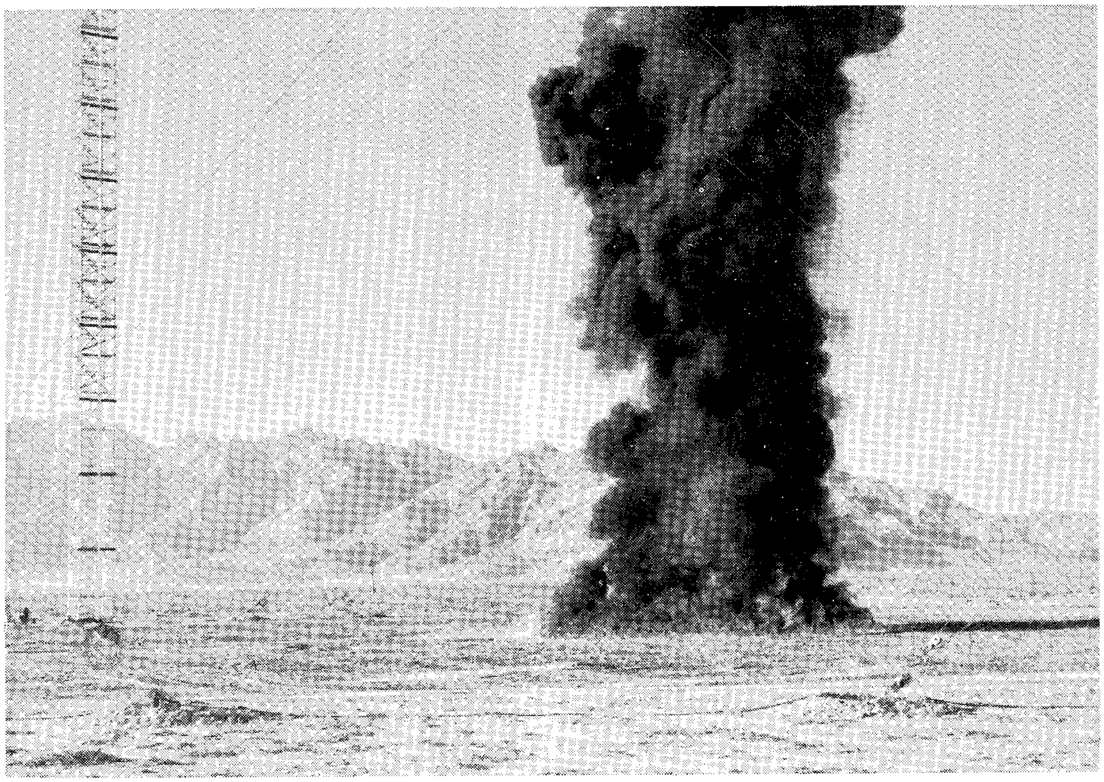

Figure 37.- ll-meter pool fire test S-1 - 1 minute.

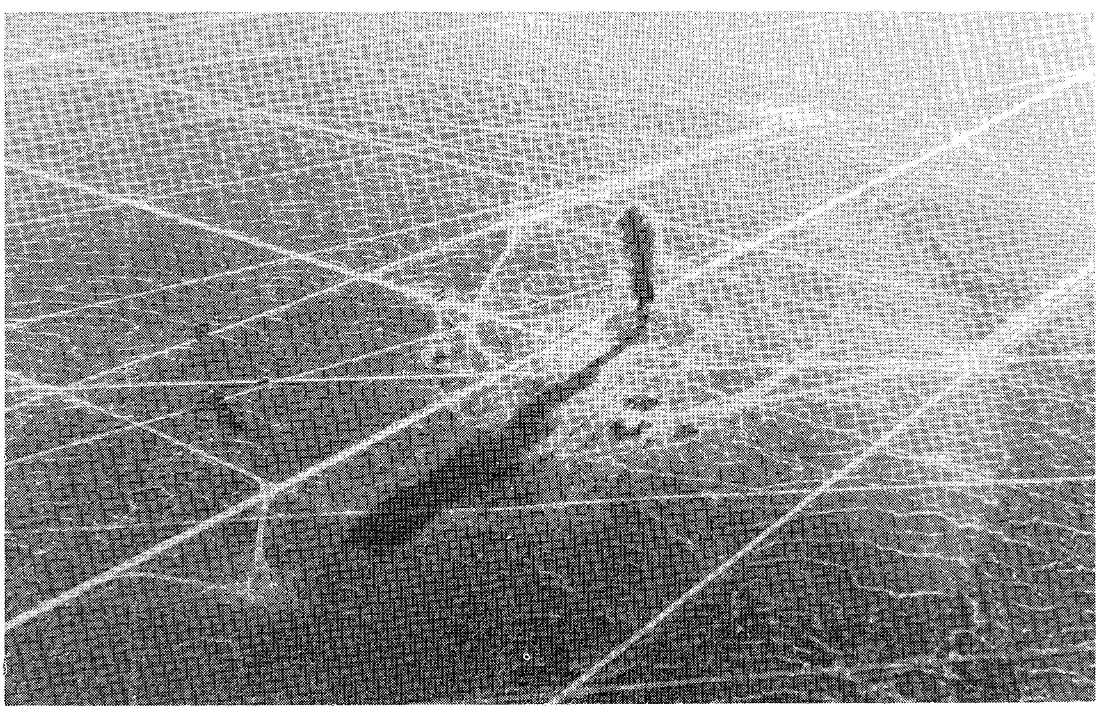

Figure 38.- ll-meter pool fire test S-1 - 20 seconds, helicopter.

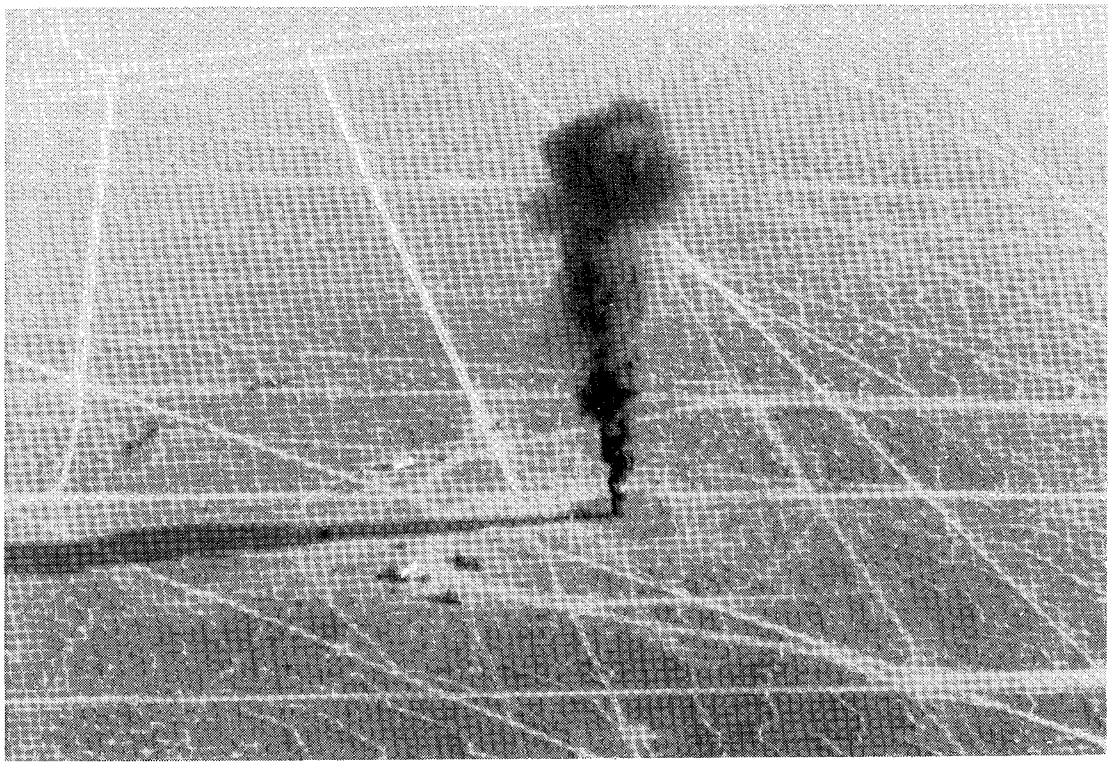

Figure 39.- 11-meter pool fire test S-1 - 50 seconds, helicopter.

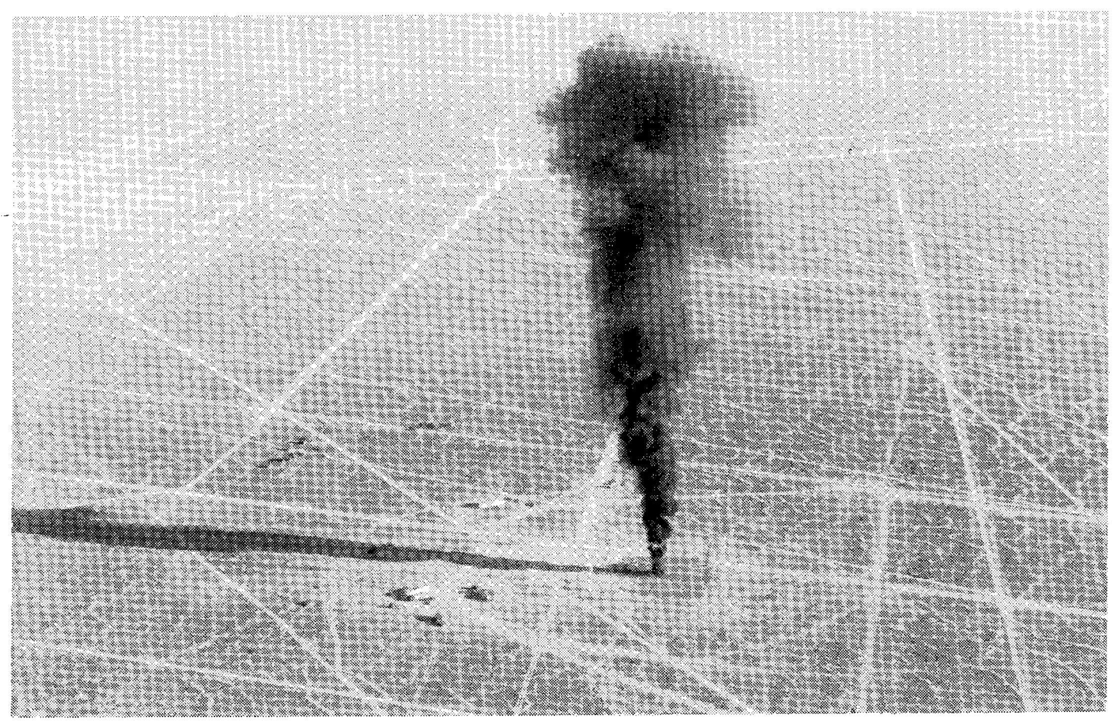

Figure 40.- 11-meter pool fire test S-1 - 80 seconds, helicopter.

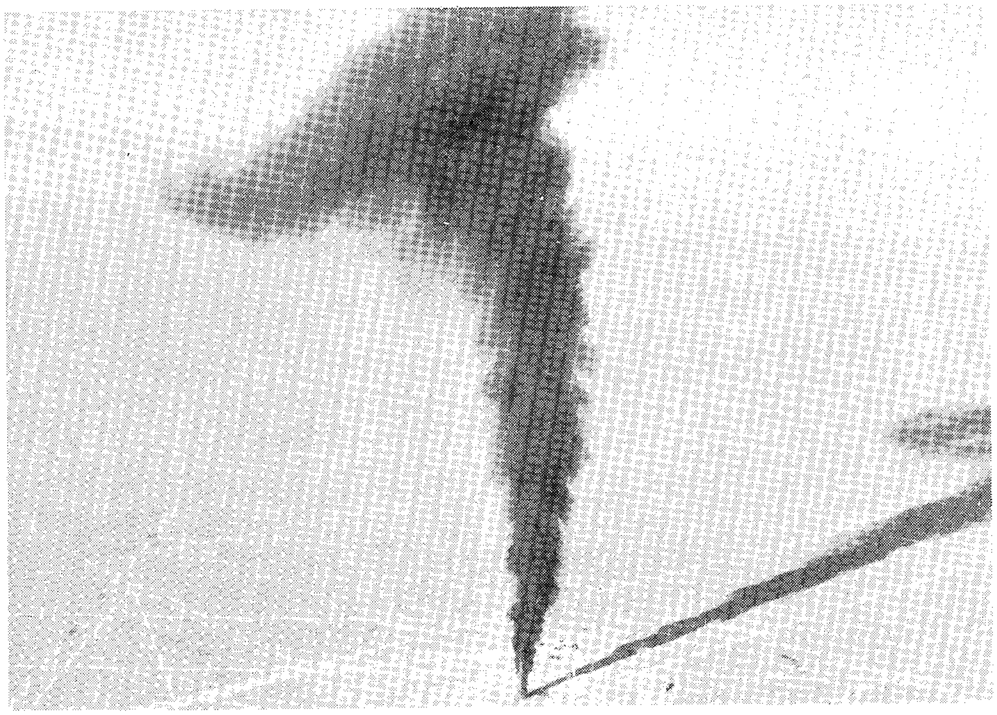

Figure 41.- 11-meter pool fire test S-1 - 3 minutes 30 seconds, helicopter.

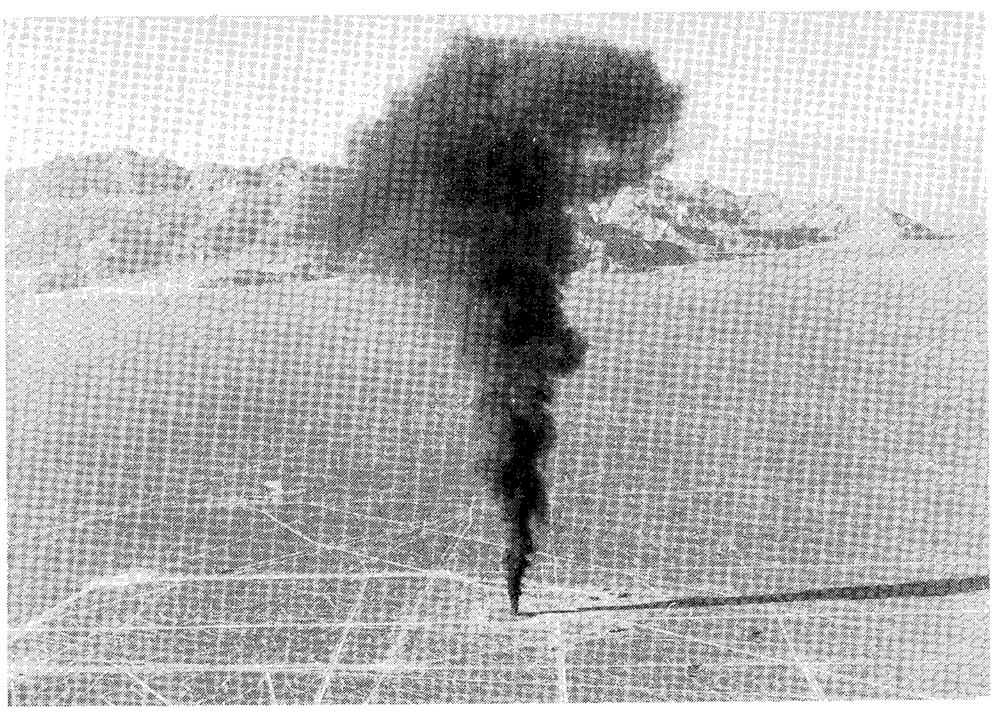

Figure 42.- 11-meter pool fire test S-1 - 4 minutes 45 seconds, helicopter.

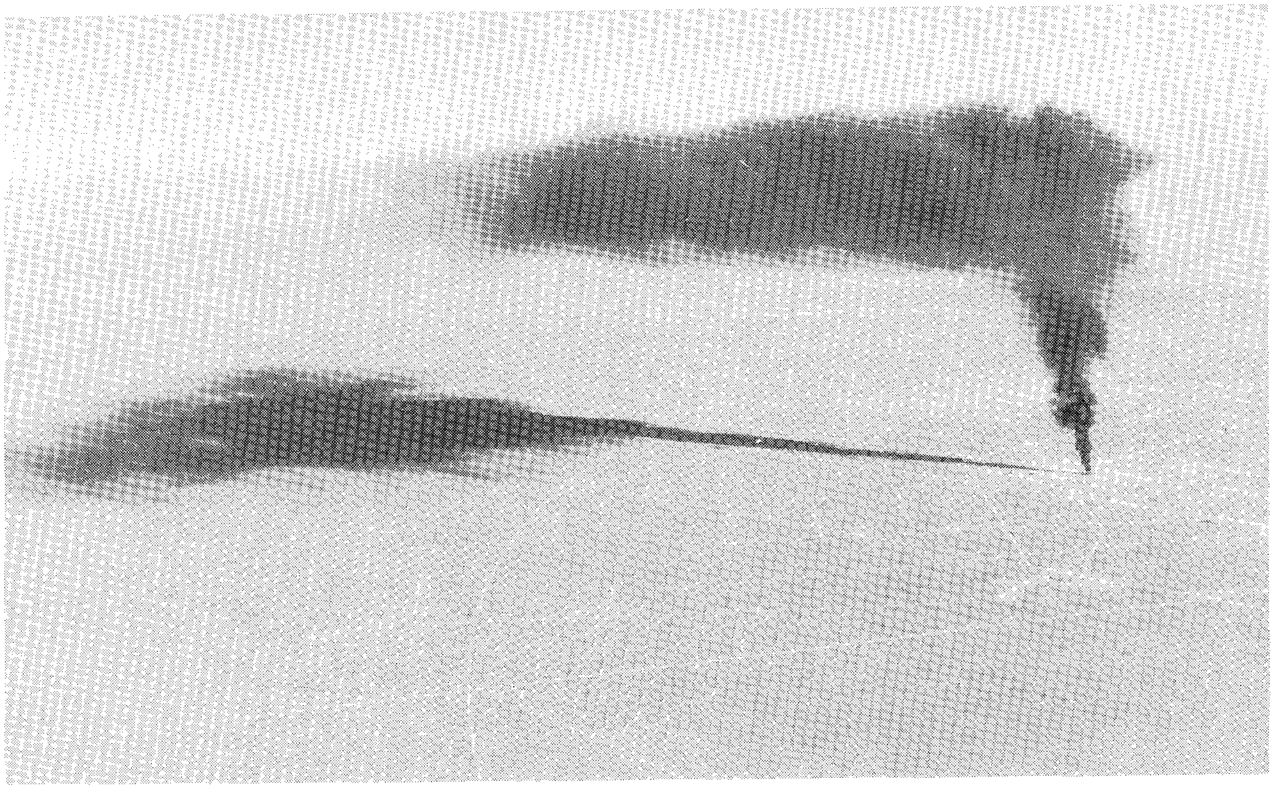

Figure 43.- 11-meter pool fire test S-1 - 14 minutes, helicopter.

TRIAL	WINDSPEED (METERS/SEC)	WIND DIRECTION (DEGREES)	STABILITY CATEGORY
D-1	6.4	360	NEUTRAL
D-2	5.8	289	NEUTRAL
D-3	5.3	326	NEUTRAL
S-1	< 1.0	VARIABLE	STABLE
S-2	< 2.0	VARIABLE	STABLE

Figure 44.- Meteorological summary - measurements made during burn time at 8 meters above ground upwind of fire location.

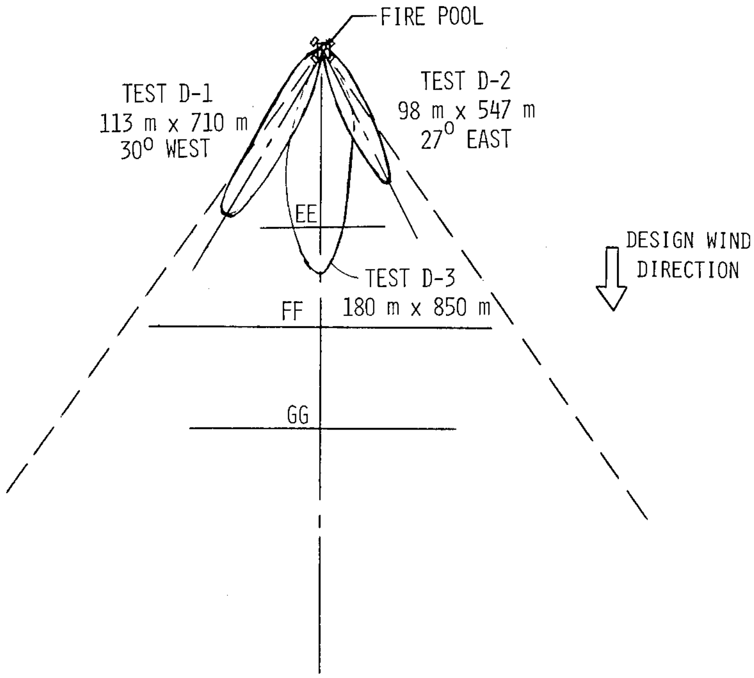

Figure 45.- Ground footprints of composite strip fallout downwind.

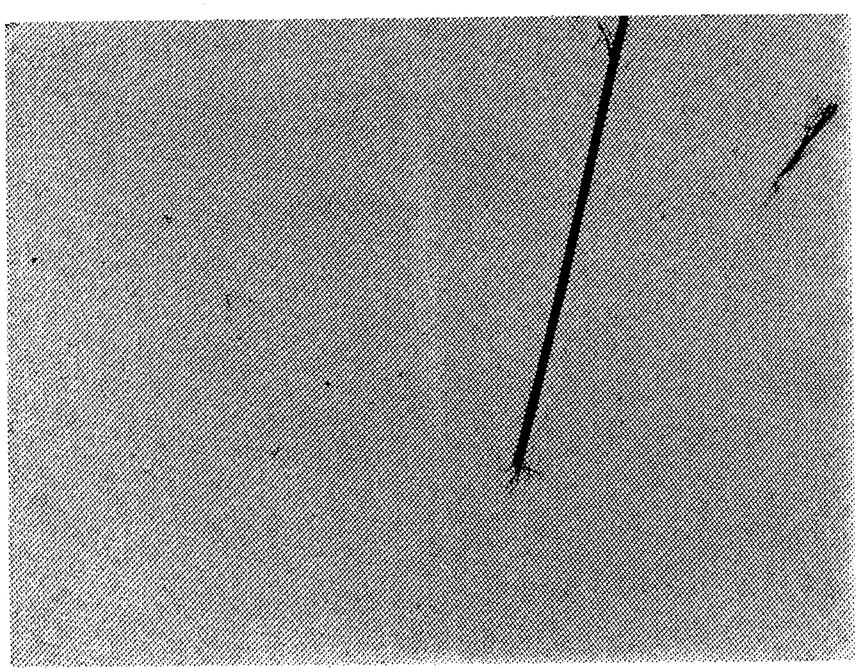

Figure 46.- Two fiber strips deposited on Jacob's ladder mesh viewgraph at Dugway outdoor fire test D-3.

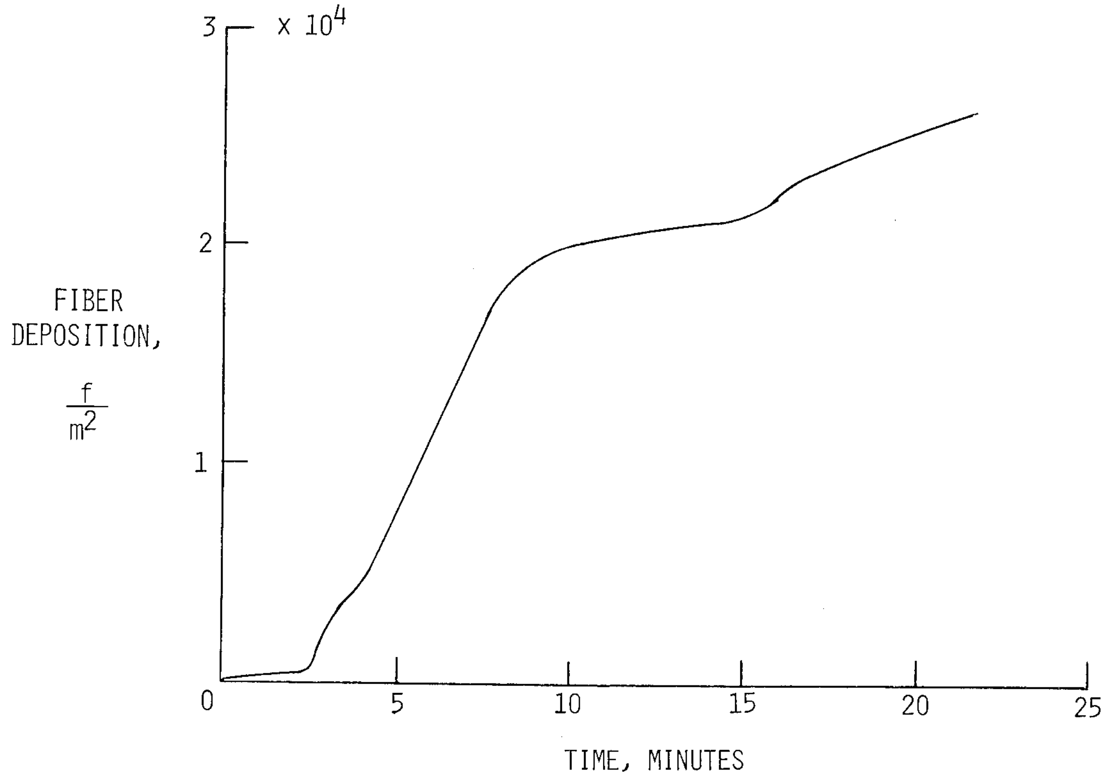

Figure 47.- Fiber counting with time from Jacob's ladder Schrader grid at Dugway outdoor fire test D-3.

TEST	CARBON FIBER MASS IN FIRE, kg	RELEASED FIBERS: TOTAL NUMBER	AVERAGE LENGTH mm	AVERAGE DIAMETER μm	SINGLE FIBERS RELEASED g	%
D-1	31.8	1.0×10^8	4.9	4.8	32	0.10
D-2	31.8	1.4×10^8	4.3	4.5	40	0.12
D-3	52.0	0.8×10^8	5.1	4.2	28	0.05
S-1	34.9	2.9×10^8	2.3	4.3	45	0.13
S-2	31.8	2.0×10^8	--	--	--	--

Figure 48.- Preliminary estimate of single carbon fibers released at Dugway outdoor fire tests.

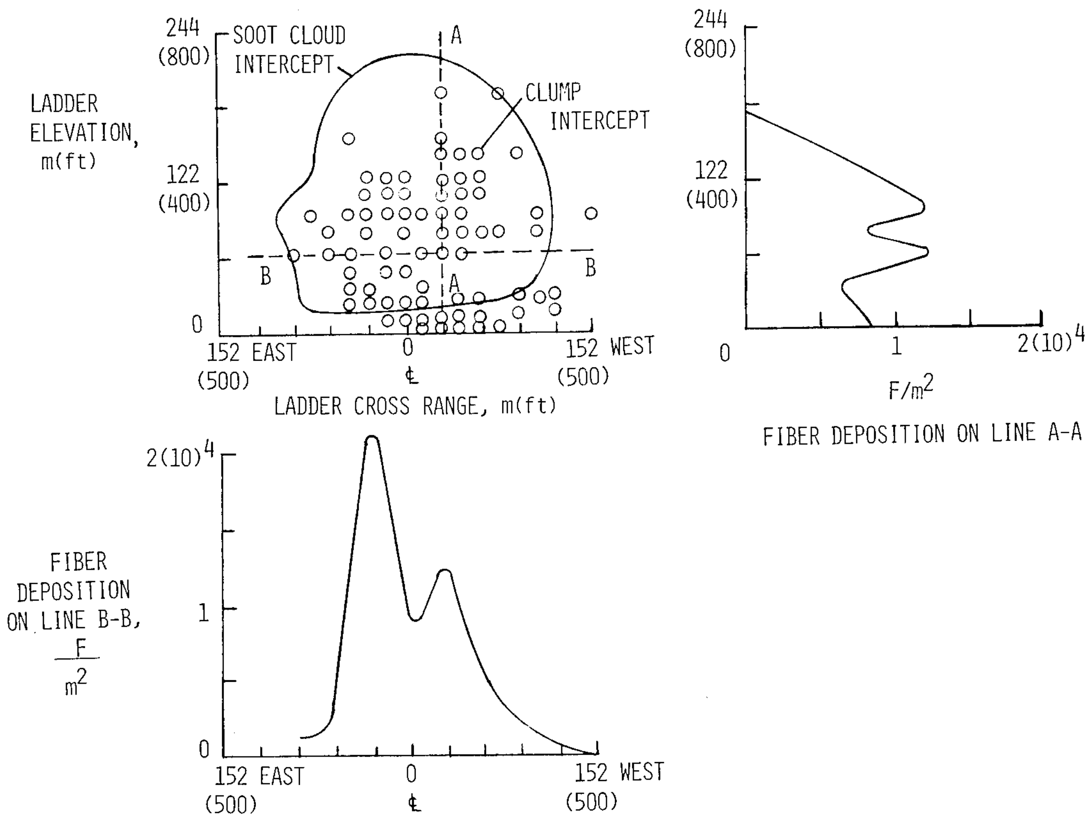

Figure 49.- Fiber counts from Jacob's ladder mesh viewgraphs at Dugway outdoor fire test D-3.

DOWN RANGE DISTANCE (METERS)	MAXIMUM EXPOSURE LEVELS (FIBER · SECS/M³)		
	TRIAL D-1	TRIAL D-2	TRIAL D-3
200	6400	2200	3300
1000	900	1400	770
2200	180	220	550
3800	70	450	210
5500	290	490	210
10200	250	580	770
19200	290	180	130

Figure 50.- Exposure levels as a function of downwind distance.

- FIBER RELEASE

  SHOCK TUBE 0.5% MAX, FORCED

  OUTDOORS 0.13% MAX

  ∴ 1% FOR RISK CALCULATIONS IS CONSERVATIVE

- FIBER LENGTH (FIBERS GREATER THAN 1 MM AVERAGE)

  SHOCK TUBE 2.0 MM AVERAGE

  OUTDOORS 5.1 MM AVERAGE

  ∴ 3 MM USED FOR RISK CALCULATIONS IS BRACKETED

- EQUIPMENT VULNERABILITY TO FIRE-RELEASED FIBERS

  - NEARLY IDENTICAL TO FIBER CHAMBER TESTS

  - JUSTIFIES USE OF FIBER CHAMBER TEST DATA IN RISK CALCULATION

Figure 51.- Tentative conclusions - large scale test results.

SURVEYS OF FACILITIES FOR THE POTENTIAL EFFECTS FROM THE FALLOUT OF AIRBORNE GRAPHITE FIBERS

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The Bionetics Corporation

The surveys of facilities which covered a representative cross section of the American workplace provided a necessary technical bridge-of-data between the analytical models and the actual working operations. The United States generates a volume of economic data through agencies such as the Bureau of the Census and organizations such as the Chamber of Commerce. Economic modeling must utilize such data in evaluating the potential effects of fiber induced failures. The working operations within the United States generally recognize the potential for a failure within items of electrical equipment and usually take some precaution even if it only amounts to keeping some spare light bulbs. Since airborne graphite fibers have the potential to cause electrical failures, the surveys had to provide the three interrelated elements of data as outlined in Figure 1. The response to a failure in an item of electrical equipment implies an economic impact. The failure site must be located, the failure cleared, and the item repaired. During that period of time operators may be idled, product can be damaged, delayed or both. Such considerations become the basis for assigning a cost to a potential fiber induced failure. The survey effort made an early recognition that failures in some items of equipment could impact lives and these areas received the necessary priority. The third element of data addressed the nature of the operation performed. Airborne fibers represent an increment in the total environment at the workplace and many operations must contend with harsh or unusual environmental conditions. The need for an environmental control as dictated by the workplace could bar the entry of fibers, or conceivably even make the operation more sensitive to fibers.

Surveys of facilities had to cover a representative cross section of the workplaces in the United States; the survey teams made a total of 62 visits to the locations summarized in Figure 2. The approach to the conduct of the surveys first recognized those areas considered most sensitive to influence by airborne graphite fibers and then utilized the result from the first series to focus the direction and detail for the next. The first series of surveys concentrated on hospitals, air traffic controls, telephone exchanges, public communications and the manufacture of electronic equipment. The surveys then broadened to cover the range-of-use for equipment considered sensitive to failures from airborne graphite fibers.

The surveys of manufacturing operations utilized the data from the Bureau of the Census "Standard Industrial Classifications" (SIC) as employed in the "Census of Manufacturers." In these compilations, the census divides manufacturing into 20 general classifications each assigned a two digit code. The code extends to four digits to reach specific product areas. As an ex-

ample, acrylic fiber manufacture falls under the product designation of "Organic Fibers, Noncellulosic" SIC 2824. All "Plastic Materials Synthetics" are combined as SIC 282 and are part of the total "Chemicals and Allied Products" SIC 28. The census data summarizes total yearly values-of-shipments for each two digit SIC code and then provides a total for the nation. The 20 manufacturing operations surveyed provide a representative sampling of that portion of American industry whose functioning depends upon the use of electrical and electronic equipment. The sample surveyed includes typical industrial operations which account for 85 percent of the total national value-of-shipments as compiled in the last Census of Manufacturers (1972).

The conduct of these surveys acknowledges a cooperation and support from both governmental and private organizations. Municipalities and counties provided access to hospitals, airports, air traffic control towers and their police or fire communication centers. Cooperating federal agencies supported the surveys of air traffic control centers, Amtrak, the Post Office and a Federal Reserve Bank. The private sector supported the full range of survey work from hospitals and airlines through a representative range of manufacturing. The results from all of these surveys shaped the appropriate portions of the economic model for defining the impact cost associated with the risk analysis.

Patterns for protective measures began to show early in the survey process. Figure 3 lists the types or elements of protection which appeared. Much of the office space and a significant portion of the industrial installations require air conditioning. Many of the newer buildings are not usable without air conditioning because their construction does not permit adequate ventilation by natural means. In other cases the nature of the operation performed requires the cleanliness associated with a controlled and filtered ventilation system. Potentially sensitive items such as computers, data processors, signal generators and electronic test racks often impose requirements on temperature controls or shielding which result in specialized isolated installations. For much of the manufacturing industries, the operating environment at the workplaces becomes hostile to electrical and electronic equipment. Such operating environments involve sprays from cutting fluids, corrosive fumes, even explosive atmospheres. The operation of electronic equipment under such conditions requires either tight cabinets or coated circuit boards. In some operations even the best electrical devices can wear, drift, or change in some way that requires attention. Such operations recognize these limitations and either keep a stock of spare parts or employ multiple installations.

The survey program identified ten areas where an electrical failure could impose a major impact. Each of these areas had recognized environmental constraints which would influence their interactions with airborne fibers. Figure 4 summarizes these areas in terms of the concern, the operating environment, the protective measures currently in place and the effect such measures would have on the ingestion of airborne graphite fibers.

The compromise of life-supporting electrical equipment in hospital operating rooms or intensive care units became one of the first major concerns. A patient in an operating room or an ICU must have protection from airborne micro-organisms and a range of ingestible contaminants. In recognition, the

Hill-Burton act which provides federal funding to hospitals also imposes the requirement for high efficiency dust removal filtration in such ventilating systems. High efficiency dust removal filters and filters classified as High Efficiency Particle Arrest (HEPA) effectively bar the entrance of airborne fibers; both types are now in hospital service. For patients in the regular hospital areas, the electronic equipment provides monitoring or support for a specific function. Here, the quantity of bedding in a hospital imposes a lint laden environment. Cases or cabinets which protect against lint also protect against the entry of graphite fibers.

Ground control of aircraft represents a second area where an electrical failure could have a serious impact. The combination of transmitters, displays, and signal conditioning equipment impose thermal loads which result in dedicated air conditioning systems for towers and area air traffic control centers. Remotely mounted beacons and transmitters must be protected from the weather, and these items have particular needs for radio frequency (RF) shielding or isolation. The net result of the combination either prevents fibers from entering the area or prevents fibers from entering a cabinet.

A third area involving a potential hazard to life could be the failure of a communication system in responding to emergency situations such as fires, accidents or even natural disasters. The communication links between a dispatcher and remote vehicles require the use of redundant installations. Communities must be capable of responding to more than one call at a time; thus more than one dispatching radio communicates with more than one remote vehicle. Cities face the problem of signals reflected from buildings and these effects lead to the provision of even more redundancy in the system for communicating with vehicles. (One city employs an electronic logic system which samples a number of radio paths and then selects the one with the best signal quality). Within a police car or fire truck, "harsh" describes the normal environment for an electronic unit in terms of heat, vibration, moisture and corrosive road dirt. The packaging of electronics necessary for successful operation in road vehicles also makes them invulnerable to graphite fibers.

The recent fire in a New York City Central Telephone Exchange raised the concern for a failure incident which could block the operation of a telephone switching center. Surveys have shown that the older stations are more open while the newer electronic systems need the advantages of a closed recirculating air conditioning system. All new construction will have controlled ventilation. It appears that fibers could get into the older stations and potentially interrupt a switching function. On the other hand, telephone stations represent numbers of identical installations each performing the same task. Single fibers could cause wrong numbers or stalled switching in one or more individual elements, but not upset the entire exchange at one time.

The history of blackouts in the Northeast leads to a concern for the circuitry which controls power generation stations, in particular fossil fueled plants. Such installations live with fly ash, and in addition, coal fired plants live with coal dust. Practical considerations led to isolated control rooms with

the electrical portions of control circuits contained within the control rooms. The isolation afforded by the control rooms in older stations may admit some airborne fibers. Such stations use voltages in the range 125-200 volts in their control elements; single fibers are not considered capable of precipitating a damaging failure at such voltages. The newer installations employ digital computers as active elements in the control systems. The corresponding ventilation systems employ more than one stage of air filtration with the second stage specified as a high efficiency dust remover. Such systems effectively isolate the control room from the rest of the generation station.

The financial community and a segment of the manufacturing community depend upon data and records stored in computers. A failure which compromises such records represents a major impact. The term "computer room" as an environmentally controlled area reflects the history of usage for electronic computers. Practical considerations of heat generation and access for cabling lead to installations with dropped ceilings, raised floors and a separate air conditioning system employing filters for dust and lint control. The computer electronics generate heat, the printers can be noisy and tape readers are sensitive to airborne dirt and dust. The trend toward smaller computers has not changed the manner of installation or the needs for protection. Computer manufacturers currently specify a minimum value for the dust removal efficiency of the air conditioning filters, and at these minimum values filters are effective barriers to airborne fibers. While airborne fibers may enter areas containing items such as point-of-sale cash registers or local terminals the main-frame installations appear environmentally isolated.

"Continuous process" describes the manufacture of such items as paper, textile fibers, industrial chemicals, petroleum refining, etc. For such an installation the loss of control at one location could stop the entire operation, and a restart could be costly. Control for such operations depends upon systems built up of specialized elements and displays with the control stations often standing alongside the operating line. The local environment can be benign, just wet, corrosive, or even explosive. A long roster of American companies manufacture control related equipment; most represent specialty items with but a few firms providing the major portions of the integrated control systems used in the continuous process industries. A canvass of the principal manufacturers of control system elements revealed that each recognized the potential applications of his equipment and designed accordingly. One assumed every unit would see service in the extremely corrosive environment of a pulp mill. All circuit boards received a conformal coating. A second manufacturer utilized tightly sealed cases. A third used a mix of both depending upon the installation. The installation of electrical circuitry into industrial buildings utilizes standardized classes of enclosures as defined by the National Electrical Manufacturers Association (NEMA). The classes range from General Purpose Indoor (NEMA Class 1) as the most open and continues through degrees of sealing for rain, dust, immersion and explosive atmospheres. NEMA Class #12 appears as the industrial standard for an installation which needs protection from both moisture and dust. The nature of a continuous process operation seems to preclude any exposure of electrical circuit elements to the ambient environment.

"Automated production" can be envisioned as those operations which machine metal, fill bottles, seal cans or wrap packages. A number of closely controlled steps proceed in sequence. The disruption of one step halts all the others, and an unscheduled halt could result in a damaged product. The environment in such lines can range from benign (as in some food processing lines) up through cutting fluid sprays to explosive as in a line which filled aerosol cans with a hydrocarbon propellant. Automated machining lines employ numerically controlled machine tools and some employ dedicated computers. Equipment operating in such environments finds the need to place high efficiency filters in the ventilated cases or to completely seal the cases. Reviews of maintenance records for machining lines show that sealed units have minimum calls. The records also show that when the environment includes metal chips, a damaged seal usually results in an electrical failure caused by the ingestion of conductive debris. For such installations the measures which seal out the ambient contaminants also seal out airborne graphite fibers.

Assembly line operations involve products which range from automobiles to washing machines. Failure at any step in an assembly line could halt the entire line and idle the work force. Where electrical items play critical roles in the process, the surveys have found either sealed cases, multiple units or ready spares. For some assembly lines such as televisions, or home appliances, a degree of cleanliness becomes a requirement. Cleanliness tends to limit the potential for a line halt caused by graphite fibers. In summary, assembly lines require continuous monitor for potential stoppages or bottlenecks. Problems receive prompt attention. Operations in unprotected environments such as the assembly of automobiles requires ready spares or redundant installations; other assembly lines have the protection afforded by air-conditioning. As a result assembly line operations do not appear vulnerable to stoppage by airborne graphite fibers.

The results from surveys can be summarized in terms of events which will not happen. Figure 5 lists the principal findings for services, for utilities and for commercial institutions. Life-critical functions appear to have the necessary degree of environmental isolation to preclude a threat to life. The police, fire and rescue communication links will function. Generating stations do not appear vulnerable. For telephones one could get a wrong number or not complete a call on the first try, but that happens even now. The banks, the brokerage houses and similar operations appear to have adequate protections.

Figure 5 summarizes the results from surveying manufacturing installations, and these show a range in potential for impact. The potential for impact may be addressed in terms of industry types as defined by the two digit SIC code. Eight of the SIC classes for manufacturing industry operate under environmental conditions which result in an effective isolation of electrical items from the ambient environment. The Food Processing Industry, SIC 20, lives with a cleanliness requirement. In these industries operations must proceed in environmentally controlled areas. As examples,in a frozen food plant, equipment has to proceed in refrigerated areas, meat packing equipment has to permit wash down, etc.

The printing plants, SIC 27, must control humidity just to keep paper moving through their presses. Their sensitive electrical equipment becomes environmentally isolated. The other 6 classes represent the continuous process industries working in corrosive environments. The two classes of manufacturing which machine metal and thereby must contend with conductive debris include the fabrication of machinery and the fabrication portion of the automobile, airplane, and railroad equipment industries. These two together with the first eight show value-of-shipments totalling 55 percent of all manufacturing as compiled by the last Census of Manufacturers.

The manufacturer of electronic and electrical circuitry items requires a degree of cleanliness for control of contaminants and debris. These factories take advantage of air conditioning or air filtration as a measure of control. The air conditioning reduces the probability for entry of fibers and thereby reduces the economic impact for another 10 percent of industrial installation. Where assembly lines and fabrication lines operate with ready spares such as observed in the controllers for spot welding of auto bodies, the potential for economic impact is also reduced. Another 7 percent of American industry carries this type of protection.

The total experience from surveying a cross section of the workplaces in the United States leads to a series of conclusions relative to the degree of economic impact which can result from the entry of airborne graphite fiber into a workplace. Figure 6 lists these conclusions. The life critical areas may be excluded from any impact considerations. Emergency services, utilities and commercial institutions could suffer non-disruptive failures. For the manufacturing industries half the total value-of-shipments comes from factories which may be eliminated from impact projections. The surveys did not see any failure sites within factories where airborne fibers could cause a total factory shutdown. For manufacturing, impact will be in terms of single machines. The losses will be costs for troubleshooting and repair with some operators temporarily idled and some product damage or production loss. The surveys found that manufacturing operations must contend with a number of randomly occurring failures in items of electrical equipment. The potential number of additional failures caused by fibers would not be recognized against the background of the present random failures. In a discussion after a tour, one plant engineer summarized the potential impact in the words, "We probably would not even know if it had happened."

THE SURVEYS OF PUBLIC, UTILITY, COMMERCIAL AND INDUSTRIAL INSTALLATIONS PROVIDED THREE ELEMENTS OF DATA:

- ECONOMIC MODELLING: DATA TO ESTIMATE THE IMPACT OF A FIBER INDUCED FAILURE AS COSTS OF REPAIR, REPLACE, LOST TIME, ETC.
- HAZARD SENSITIVITY: DATA TO IDENTIFY WAYS FIBERS COULD INTERFERE WITH LIFE CRITICAL OR EMERGENCY SERVICES.
- OPERATION SENSITIVITY: DATA TO DEFINE THE EFFECTS OF AN IN-PLACE PROTECTION OR HIGHLIGHT A PARTICULAR SENSITIVITY TO AIRBORNE FIBERS.

Figure 1.- Survey of facilities for potential effects from airborne graphite fiber.

1) PUBLIC SUPPORT	NO.
HOSPITALS	7
AIR TRAFFIC CONTROLS	6
AIRPORTS-AIRLINES	3
POLICE HEADQUARTERS	2
FIRE DISPATCH	2
POST OFFICES	1
TRAFFIC CONTROL	1
2) UTILITIES	
TELEPHONE EXCHANGES	3
POWER GENERATOR, DISTRIB.	3
REFUSE INCINERATORS	2
AMTRAK	1

3) COMMERCIAL INSTALLATIONS		NO.
DEPARTMENT STORES		2
FINANCIAL INSTITUTIONS		2
RADIO AND TV STATIONS		6
ANALYTICAL LABORATORIES		1
4) MANUFACTURING OPERATIONS (SIC)		
MEAT PACKING	(20)	1
TEXTILE MILL	(22)	1
GARMENTS	(23)	1
PULP AND PAPER	(26)	1
PUBLISHING	(27)	2
TEXTILE FIBERS	(28)	1
TOILETRIES	(28)	1
STEEL MILLS	(33)	2
WIRE, CABLE	(33)	1
ELECTRICAL EQUIP.	(36)	6
AUTOMOTIVE FAB/ASSY	(37)	4

Figure 2.- Summary of facilities surveyed.

- ON-SITE TECHNICAL SURVEYS COVERED 62 LOCATIONS AS PUBLIC, UTILITY, COMMERCIAL AND MANUFACTURING FACILITIES
- PRESENT OPERATING REQUIREMENTS RESULT IN FACILITY CONFIGURATIONS OR FEATURES WHICH PROTECT AGAINST FIBER ENTRY OR INTERACTIONS.

  -AIR CONDITIONED BUILDINGS WITH FILTERS FOR INTAKES AND RECIRCULATION.

  -SENSITIVE EQUIPMENT IN SEPARATE ROOMS WITH INDEPENDENT ENVIRONMENTAL CONTROL.

  -SENSITIVE EQUIPMENT IN CLOSED OR FILTERED VENTILATION CABINETS.

  -ELECTRONIC CIRCUIT BOARDS WITH CONFORMAL COATINGS.

  -FAILURE PRONE EQUIPMENT BACKED BY READY SPARES.

Figure 3.- Surveys of facilities, general findings.

AREA OF CONCERN	PRESENT OPERATING CONCERN
1. HOSPITAL OPERATING ROOMS AND CRITICAL CARE AREAS	. AIRBORNE INFECTIONS CONTAMINANTS
2. HOSPITAL ROOMS	. LINT
3. AIR TRAFFIC CONTROL TOWERS AND EQUIPMENT	. OPERATING TEMPERATURE . ELECTROMAGNETIC INTERFERENCE
4. POLICE/FIRE EMERGENCY COMMUNICATION SYSTEMS	. RF SIGNAL QUALITY . IN-VEHICLE OPERATION
5. TELEPHONE EXCHANGE CENTERS	. AIRBORNE PARTICULATES . NEED FOR MULTIPLE INSTALLATION
6. POWER GENERATION CONTROL SYSTEMS	. FUEL DUST . FLY ASH
7. DATA STORED IN CENTRAL COMPUTERS	. HEAT GENERATION - HUMIDITY . AIRBORNE CONTAMINANTS
8. CONTINUOUS PROCESS CONTROL SYSTEMS	. CORROSIVE FLUIDS AND SPRAYS . EXPLOSIVE ATMOSPHERES
9. AUTOMATED PRODUCTION CONTROL SYSTEMS	. CUTTING FLUID SPRAY . EXPLOSIVE/CORROSIVE ATMOSPHERES
10. ASSEMBLY LINE OPERATING AND CONTROL ELEMENTS	. EQUIPMENT BREAKDOWN . AIRBORNE CONTAMINANTS

Figure 4.- Critical failure areas and present protection.

PRESENT PROTECTION	EFFECT
. "ABSOLUTE" AIR FILTRATION (HILL-BURTON REQUIREMENT)	. FIBERS DO NOT ENTER AREAS
. CLOSED CASES	. ITEMS NOT VULNERABLE
. RECIRCULATING FILTERED AIR . RF SHIELDED CABINETS	. FIBERS DO NOT ENTER AREA . ITEMS NOT VULNERABLE
. MULTIPLE UNITS . CLOSED CASES	. SYSTEM ACCEPTS SINGLE FAILURES . ITEMS NOT VULNERABLE
. RECIRCULATING FILTERED AIR . REDUNDANT EQUIPMENT	. LIMITED FIBER ENTRY . SYSTEM ACCEPTS SINGLE FAILURES
. CONTROL ROOMS SEPARATED WITH RECIRCULATING FILTERED AIR	. OLDER STATIONS: LIMITED FIBER ENTRY CONTROL VOLTAGES NOT SENSITIVE TO FIBERS . NEW STATIONS: ENVIRONMENTALLY ISOLATED
. ROOM-WITHIN-ROOMS . RECIRCULATING FILTERED AIR	. FIBERS DO NOT ENTER COMPUTER AREAS
. COATED CIRCUIT BOARDS . SEALED CASES (NEMA #12)	. NO ELECTRICAL CIRCUIT ELEMENTS OPEN TO FIBERS
. HIGH EFFICIENCY FILTERS OR SEALED CASES	. FIBERS DO NOT ENTER CASES
. READY SPARES . RECIRCULATING FILTERED AIR	. SYSTEM ACCEPTS SINGLE FAILURES . LIMITED FIBER ENTRY

Figure 4.- Concluded.

	PERCENT OF NATIONAL VALUE-OF-SHIPMENTS
• INDUSTRIAL OPERATIONS	
- NO IMPACT BECAUSE OF PROTECTION FROM PRESENT OPERATION ENVIRONMENT:	40
SIC 20 FOOD, 22 TEXTILE MILLS, 26 PAPER, 27 PRINTING, 28 CHEMICALS, 29 PETROLEUM AND COAL, 30 RUBBER, 31 LEATHER	
- NO IMPACT BECAUSE OPERATIONS NEED LOCAL PROTECTION FROM CUTTING FLUIDS, CONTAMINANTS:	15
SIC 35 MACHINERY, 37 TRANSPORTATION (PARTIAL)	
- REDUCED IMPACT BECAUSE OPERATIONS NEED AIRCONDITIONING OR SOME CONTROL OF AMBIENT CONDITIONS:	10
SIC 36 ELECTRICAL, 38 INSTRUMENTS	
- REDUCED IMPACT BECAUSE OPERATIONS ARE SUPPORTED BY READY SPARES:	7
SIC 37 TRANSPORTATION (PARTIAL) SIC 33 PRIMARY METAL (PARTIAL)	

- LIFE CRITICAL FUNCTIONS HAVE IN-PLACE PROTECTIONS AGAINST THE ENTRY OF AIRBORNE GRAPHITE FIBERS.
- EMERGENCY SERVICES WILL NOT BE INTERRUPTED BY AIRBORNE GRAPHITE FIBERS.
- ELECTRICAL UTILITIES WILL NOT BE DISRUPTED BY AIRBORNE GRAPHITE FIBERS.
- TELEPHONE SYSTEMS WILL NOT BE DISABLED BY AIRBORNE GRAPHITE FIBERS.
- COMMERCIAL INSTITUTIONS WILL NOT LOSE THEIR ESSENTIAL RECORDS STORED IN COMPUTERS.

Figure 5.- Results from surveys.

- LIFE CRITICAL FUNCTIONS: EXCLUDE FROM IMPACT PROJECTIONS.
- EMERGENCY SERVICES: ECONOMIC IMPACT LIMITED TO SINGLE ITEMS OF EQUIPMENT.
- UTILITIES: ECONOMIC IMPACT IN TERMS OF A LOCAL OUTAGE/REPAIR.
- COMMERCIAL INSTITUTIONS: IMPACT IN TERMS OF PERIPHERAL EQUIPMENT.
- INDUSTRIAL INSTALLATIONS:
  - FOR HALF OF INDUSTRY, NO ECONOMIC IMPACT.
  - NO FACTORY SHUTDOWNS.
  - ECONOMIC IMPACT IN TERMS OF SINGLE FAILURES AND REPAIRS.

Figure 6.- Conclusions.

ASSESSMENT OF THE RISK DUE TO RELEASE OF CARBON FIBER IN CIVIL AIRCRAFT ACCIDENTS

PHASE II REPORT

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SUMMARY

Under Contract NAS1-15379, ORI, Inc. investigated the risk associated with release of graphite fibers following a commercial aircraft accident and fire. The computer simulation model developed in Phase I was refined in Phase II. Additional experimental data has been made available. Phase II results indicate that the risk, considerably lower than that obtained in Phase I, is relatively small.

INTRODUCTION

This paper summarizes ORI's Phase II investigation of the risk associated with the potential use of carbon fiber composite material in commercial jet aircraft. In Phase I a simulation model was developed to generate risk profiles for several airports; the risk profiles show the probability that the cost due to accidents in any year exceeds a given amount. The computer model simulates aircraft accidents with fire, release of fibers, their downwind transport and infiltration of buildings, equipment failures, and resulting economic impact. The individual airport results were combined to yield the national risk profile. Phase II was conducted to examine the risk with more precision, and incorporate previously unavailable experimental data. These relationships are illustrated in Figure 1.

The structure of the ORI Airport Risk Model is illustrated in Figure 2. The principal steps in the simulation of each accident are illustrated in Figure 3; each is discussed in turn in this paper. The major focus is on those elements of the analysis into which changes were introduced in Phase II, principally:

- o Availability of detailed analyses of jet aircraft accidents with fire
- o Incorporation of new experimental data for the amount of carbon fiber released in a "burn"
- o Generalization of the ORI transport and diffusion model

- New evidence indicating high filter efficiency relative to carbon fibers
- Recent experimental values for equipment failure parameters
- Introduction of a more detailed costing model
- A new national risk assessment model facilitating the computation of statistical confidence limits.

The report covers these items as well as presenting brief descriptions of all other elements of the risk analysis methodology. Phase II results are compared to the previous Phase I results.

ACCIDENT WITH FIRE/RELEASE OF CF

In Phase I, ORI conducted a limited analysis of individual aircraft accident reports and summary data available through the National Transportation Safety Board. In Phase II, under NASA auspices, the major aircraft manufacturers completed a detailed analysis of approximately 100 jet aircraft accidents in which fire played a part. These analyses provided estimates of the damage to each major aircraft structural component. It was determined that the annual fire-accident rate pertinent to the risk assessment was 3.8; this has been accepted as the best estimate available for the 1993 scenario. For the risk assessment calculation we are only concerned with aircraft containing composite material, estimated to be about 70 percent of the 1993 fleet, for a resulting national mean number of carbon-fiber aircraft accidents with fire of 2.6 per year.

The calculation proceeds one aircraft size at a time. Accordingly, for airport A and aircraft of size S, we estimate the annual accident-with-fire rate by:

$$\frac{N_{A,S}}{\sum\limits_{A}\sum\limits_{S} N_{A,S}} \times 2.6 \qquad (1)$$

where $N_{A,S}$ is the number of operations of aircraft of size S at airport A; thus the sum represents all operations in the U.S. The model computes the expression (1) from appropriate input data, and then draws a random sample from a Poisson distribution with this mean value in each replication.

In a related effort the principal aircraft manufacturers, NASA, and NASA's risk assessment contractors prepared estimates of the projected changes in the commercial aircraft fleet from now to 1993. These schedules included projected utilization of graphite fiber composite in each component. These data were combined with the accident analysis results to provide estimates of the amount of composite that would be involved in a fire following an accident to any of the projected new aircraft. In effect, for each projected aircraft type we computed the sum

$$\sum_i \text{(fraction consumed)}_i \times \text{(amount of composite)}_i$$

for all accidents in the airframers' analysis, where the index i refers to an aircraft component. Thus, for one aircraft type, defined by a distribution of composite material, we have the total composite that would have been consumed in each of the historical accidents. These results were then used as the probability distribution for the amount of composite involved in the fire. In each simulated accident the model determines the type of aircraft involved, based on the relative numbers of the different types in the fleet. For that type aircraft the model then draws the amount of composite involved from the distribution just described. It is then assumed that one percent of the carbon is released as 3-mm single fibers. In those accidents in which an explosion occurs, an additional two-and-a-half percent is assumed to be released due to the agitation of the composite material. These input assumptions are based on experimental evidence generated after completion of Phase I. The model also selects a random accident location based on analysis of the accident data.

PLUME

The graphite fiber release starts with an aircraft accident leading to a fire; the fire is fed by the aircraft fuel. As a result of the fire some fraction of the aircraft is consumed. The estimation of this fraction, and the ultimate amount of fiber released were discussed in the preceding section. As a consequence of the fire a hot buoyant plume is formed that rises to a "stabilization" height which is a function of the energy available, the wind speed, and the atmospheric stability. The graphite fibers enter the buoyant plume and are lifted to the stabilization height.

Plume Height Calculation

As in Phase I, calculation of the plume rise (or elevation), H, at stabilization from an open fire follows the work of Briggs (Ref. 1). The height of the plume, in meters, is given by:

$$H = 2.9\ (F/us)^{1/3} \qquad (2)$$

for stable conditions, and

$$H = 1.6F^{1/3}u^{-1}x^{2/3}, \text{ when } x < 3.5x^* \qquad (3)$$

$$H = 1.6F^{1/3}u^{-1}(3.5x^*)^{2/3}, \text{ when } x > 3.5x^* \qquad (4)$$

for neutral or unstable conditions, where u is the mean wind speed in meters per second and:

$$x^* = 14F^{5/8}, \text{ when } F < 55$$

$$x^* = 34F^{2/5}, \text{ when } F > 55$$

The buoyancy flux parameter, F, appearing in the above equations, is given by

$$F = \frac{gQ_R}{\pi C_p \rho T}$$

where:

g = acceleration of gravity, 9.8 m/sec ^{2}

Q_R = heat emission rate, kcal/sec

C_P = specific heat of air at constant pressure,

.2391 kcal/kg$^{\circ}$K

ρ = atmospheric density, 1.239 kg/m^3

T = ambient temperature, $^{\circ}$K.

The atmospheric stability parameter, s, is defined by:

$$s = \frac{g}{T}\frac{\partial\theta}{\partial z}$$

where:

$\frac{\partial\theta}{\partial z}$ = gradient of potential temperature, 0.35°/km for stable conditions.

Heat Emission Rate

In order to use the Briggs formulas, we must specify Q_R, the heat emission rate for a burning aircraft; this is, in turn, the product of the rate measured, gallons per unit time, and the fuel heat content per gallon. In Phase I a standard burn rate was used, based on experimental data. In Phase II we were able to turn to the detailed fire-accident analysis previously referred to. In this case it was possible to estimate the fuel burn rate for accidents occuring during different operational phases, as well as accidents of different severity. The reported accidents involved small jet aircraft almost exclusively, so a scaling factor proportional to the relative volume of the aircraft fuel tanks, as reported in Janes (Ref. 2), was used to estimate the burn rates for other size aircraft. With these inputs we are able to determine the plume rise for accidents involving different aircraft for any combination of wind speed and stability conditions.

DOWNWIND TRANSPORT AND DIFFUSION OF FIBERS

Basic Concepts

In Phase I the "standard" EPA transport and diffusion model was adapted to the needs of the risk assessment study. The model provides for downwind transport of material in the form of a plume that diffuses simultaneously in the crosswind and vertical directions. The initial source can be elevated at a specified height. The atmosphere is characterized as being in one of several stability classes. Dispersion parameters that govern the rate of crosswind and downwind diffusion are associated with each stability class (Ref. 3). The plume rise calculations, described above, give the source height, which is then used explicitly in the transport and diffusion model.

In Phase II further extensions were made to the transport and diffusion model. These allow for multiple reflections of the diffusing particles and provide an improved mechanism for accounting for particle fallout at downwind distances that are so large that the cloud is uniformly dispersed in the vertical.

The wind speed at plume height is taken as representative of the layer in which the carbon fibers are dispersing. The standard power law may be written:

$$u = u_o \, (H/7)^p \tag{5}$$

The exponent p is assigned specific values for different stability classes. In most cases rather stringent physical conditions must be met for the plume to "punch through" an inversion. Observations indicate that this typically does not occur. It was therefore considered reasonable to assume that if the computed plume height is greater than the height of the inversion, it can be set equal to the inversion height.

When the vertical range over which the plume is mixed becomes equal to the depth of the mixed layer (below the inversion), we can assume a relatively uniform distribution of particles in the vertical. The model therefore makes the distribution of graphite fibers uniform in the vertical, from the ground surface to the base of the inversion, when σ_z becomes larger than 1.6 H_m.

ORI Diffusion Equations

With these assumptions, and the Phase II modifications to allow for multiple reflections, we obtain:

$$D(x,y,0,H') = \frac{Q}{\pi\sigma_y\sigma_z} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \left\{ \exp\left[-\frac{1}{2}\left(\frac{H'}{\sigma_z}\right)^2\right]\right.$$

$$+ r\exp\left[-\frac{1}{2}\left(\frac{H' + 2H_m}{\sigma_z}\right)^2\right] + \exp - \left[\frac{1}{2}\left(\frac{-H' + 2H_m}{\sigma_z}\right)^2\right]$$

$$+ r^2 \exp\left[-\frac{1}{2} \left(\frac{H' + 4H_m}{\sigma_z}\right)^2\right] + r\exp\left[-\frac{1}{2}\left(\frac{-H' + 4H_m}{\sigma_z}\right)^2\right]$$

$$\left. + r^2 \exp\left[-\frac{1}{2} \left(\frac{-H + 6H_m}{\sigma_z}\right)^2\right] \right\} \qquad (6)$$

where:

$D(x,y,0,H')$ = dosage at x,y,0 (receptor location) in particle-sec/m^3 for the particle size of interest

x = downwind distance from source to receptor,

y = crosswind distance from source to receptor,

u = mean wind speed, m/sec,

Q = number of particles released

σ_y = standard deviation of the wind speed in the crosswind direction, as a function of x and the stability class

σ_z = standard deviation of the wind speed in the vertical, as a function of x and the stability class

r = reflection coefficient, the fraction of particles that are reflected from the ground surface

In order to incorporate the effect of particle fallout into our calculations we adopted the tilted-plume method presented by Van der Hoven (Ref. 4). Equation (6) makes use of the effective plume height, H', given by:

$$H' = H - (v_s / u) x \tag{7}$$

At distances far enough downwind ($\sigma_z > 1.6 H_m$) that mixing results in an essentially uniform distribution of the fibers in the vertical we use:

$$D(x,y,0,H') = \frac{Q}{2.5066 \sigma_y H_m u} \exp \left[- \frac{1}{2} \left(\frac{y}{\sigma_y}\right)^2 \right] \exp \left[- \frac{v_s \, x \, (1-r)}{2uH_m} \right] \tag{8}$$

Inputs to Transport Calculation

Mixing heights were developed, as in Phase I, from climatological mean values (Ref. 5) adjusted for different stability classes (Ref. 6). Sensitivity analyses are planned to test the impact of changes in mixing height values.

In many diffusion problems it is customary to determine the location of an upwind virtual point source from which a diffusing plume would have grown to the size computed for plume stabilization. In view of the large uncertainties in other phases of the risk calculation, and our concern with effects some miles downwind from the accident site, we have set the virtual point source directly over the accident/fire site.

The reflection coefficient has been set equal to 1 at the inversion and to 0.7 at the ground.

The diffusion calculation requires input values of the dispersion parameters, σ_y and σ_z, as functions of the downwind distance, x, and the prevailing stability conditions. The standard in this case is provided by the well-known Pasquill-Gifford curves. Several investigators have questioned their universal applicability; the reader is referred to Pasquill's recent work on this subject (Ref. 7). In view of the fact that no generally accepted modification of the Pasquill-Gifford curves exists, we adopted these curves for the Phase I calculations and continued to employ them in Phase II.

The basic weather inputs required - surface wind speed and direction, and stability class - are drawn from historical data. These data were obtained from the National Weather Records Center for the airports we studied; the data provide the frequency for each combination of the three weather parameters. The simulation model makes a random draw of one of these combinations weighted by the input frequency.

TRANSFER OF FIBERS INTO INTERIOR OF STRUCTURES

Method

When a building is impinged on by a plume of carbon fibers, some of the fibers may enter the building through air conditioning or other ventilation systems and by various leakage paths. Once inside the building or enclosure, fibers will be removed by fallout and through leakage paths back to the outside. If inside air is recirculated and filtered, additional fibers will be removed. The concentration of fibers that produce failure stresses on equipments in a building or enclosure at any time may be determined from equations describing the net flow. These have been developed in a relatively simple form by Slade (Ref. 4).

In Phase I, ORI was able to show that the "transfer function" or ratio of interior to exterior exposure can be expressed as:

$$\frac{E}{E_o} = \frac{v_i}{v_o + av_s + v_r} \tag{9}$$

where:

v_i = rate at which fiber-borne air enters the building, or enclosure through both the air conditioning system and through all sources of leakage

v_o = rate at which fiber-borne air leaves the building, including that removed by recirculation

v_s = fall rate of carbon fibers

v_r = rate at which fibers are removed by recirculation filtering

a = area of space subject to fallout.

Implementation

Equation (9) formed the principal basis for the calculation of interior exposure values. It was assumed that all buildings can be adequately defined by one or more of the following categories:

1. Small Equipment Building or Van

2. Medium Equipment Building

3. Large Equipment Building or Factory

4. Equipment Room inside a building

5. Utility Room

   a) filtered

   b) unfiltered

6. Residence

   a) air conditioned

   b. not air conditioned

7. Retail/Wholesale Establishments

Design factors were associated with each category of building defined above. These design factors are used to determine the air conditioning flow rates, filter efficiencies, and air leakage rates used in Equation (9). Ventilation rates were based on standards in References 8 and 9.

Phase I values of filter effectiveness were revised to incorporate Phase II experimental results. The transfer functions shown in Table I were used in all Phase II calculations. Specific building types were associated with different categories of business and industry, as described below.

EQUIPMENT FAILURES

Failure Model

The probability of failure of equipment which is exposed to carbon fibers is obtained from the exponential expression:

$$P_F = 1 - \exp(-E/\bar{E}) \tag{10}$$

where:

P_F = probability of equipment failure

E = exposure level in the immediate vicinity of the vulnerable equipment, in fiber-seconds per cubic meter

$\bar{E}$ = average exposure causing a failure.

During Phase I, the U.S. Army Ballistics Research Laboratory (BRL) at Aberdeen, Maryland determined that experimental failure data fit an exponential failure law (Ref. 10). In Phase II it has been shown that, even for those equipments whose failures do not obey the exponential law, it is conservative to assume that the exponential law is obeyed. Typical values of the failure parameter for generic equipment types are shown in Table II.

The exposure used in Equation (10) is that directly impinging on the vulnerable equipment. When this equipment is inside a building, the interior exposure may be obtained from the exterior exposure by multiplying the exterior exposure by the appropriate transfer function (TF). Since the transfer function and the mean exposure to failure, $\overline{E}$, are constants for a particular piece of equipment in a particular building, we define a failure parameter:

$$K_{ij} = (TF)_j/\overline{E}_i \tag{11}$$

where:

K_{ij} = overall failure parameter for equipment of type i in a building of type j

$(TF)_j$ = penetration factor (transfer function) for a building of type j

$\overline{E}_i$ = mean exposure to failure for equipment of type i.

In subsequent applications, the parameter K_{ij} is substituted into Equation (10) to give the probability of failure for equipment of type i in a building of type j for any exterior exposure:

$$P_{F,ij} = 1 - \exp(-K_{ij}E_o) \tag{12}$$

Equipment Configurations

In treating typical equipment configurations it is convenient to develop expressions for the collective probability of failure of the complete configuration. In particular, if n identical equipments are in series so that a failure of one causes the entire "line" to fail, the probability that the line fails is:

$$\begin{aligned} P_F\,(\text{LINE}) &= 1-(1-P_{F,ij})^n \\ &= 1-e^{-nK_{ij}E_o} \end{aligned} \tag{13}$$

Similarly if n like equipments are in parallel, so that the operation fails only if all equipments fail, the aggregate probability of failure is:

$$P_F(\text{Operation}) = P^n_{F,ij} \tag{14}$$

The computer program that determines the impact of each simulated aircraft accident and associated release of graphite fibers uses Equations (12), (13), (14) to

estimate the probability that each business or industry in the geographical area of interest is affected.

One of the major efforts in Phase I was the characterization of each business-industry sector, defined by an SIC (Standard Industrial Classification) number, by a specific set of equipments installed in a specific building. This effort was extended and made more detailed in Phase II. A complete basic equipment configuration is shown in Figure 4; in any particular facility one or more portions of this configuration may not be present. In addition, the equipment "suit" is made specific to plant size (small, medium, or large). An example will illustrate the method. A large plant in Category 28A (comprising all 3-digit SIC code numbers under 28, basically chemical and allied products) has an internal power interface characterized by one set of input power service equipment, one distribution panel, and auxiliary power equipment. Its common module consists of two computers in parallel and two keyboard display units in parallel. The plant has 25 lines in its distributed module. Each line consists of:

- 5 high-voltage power supply units
- 5 interface units
- 5 manual controllers
- 5 minicomputers, used as controllers
- 2 high-voltage motor controllers
- 2 machine station servo-mechanisms
- 1 heater control unit
- 5 sensor units.

Similar configurations were defined for all vulnerable categories of business and industry. The data was developed as a result of an extensive literature search, augmented by site visits during Phases I and II. The different building types defined in Table I are related to the different modules of each type of vulnerable business and industry. For example, Table III associates the different building types with the major sections (modules) of plants of different size in Category 28A.

Computer Implementation

The mean exposure-to-failure values for several of the generic equipments defined above are summarized in Table II. In using these inputs the equipment-specific value of $\overline{E}$ was combined with the building-specific transfer function, in accordance with Equation (11). In order to estimate the impact on specific business and industrial complexes it was assumed that the plant is down if electric power is lost inside the plant, if the common module fails, or

if more than one half of the "lines" in the distributed module fail. Since Phase II results reported by other investigators indicated that the high-voltage power supply system is essentially invulnerable, it was assumed that an equivalent piece of equipment representing the output bushings and buss of a step-down transformer could be used to represent the possibility of an exterior power supply failure.

COSTS ASSOCIATED WITH EQUIPMENT FAILURES

Scope of Calculation

This section of the paper presents ORI's Phase II methodology for determining the costs associated with equipment failures. The most significant changes to the Phase I methodology were introduced in this part of the risk assessment calculation. Three categories of cost were defined for business and industry impacts:

- Repair of damaged electrical equipment
- Facility cleanup
- Business/industry disruption.

In the Phase I risk assessment, attention was focussed on the latter cost category using an expected value technique. In Phase II the model has been expanded to treat all the above categories explicitly, while disruption costs are now computed by a Monte Carlo process. Household equipment failures are treated as in Phase I. A completely new module has been introduced to compute the cost incurred due to repair of damaged avionics equipment.

Repair Costs

A repair cost was defined for each generic type of equipment shown in Table II. Categories of business and industry were defined by SIC code (primarily at the three-digit level) as well as by size. As described in the preceding section each facility has a specific number of each equipment type. The model computes the probability of failure for each type of equipment at a particular location; the number that fail is determined in a Monte Carlo random draw. Model inputs include the equipment repair costs. The product of the number that fail and the repair cost yields the repair costs associated with that kind of equipment at that location.

Facility Clean-Up Costs

Estimates of facility clean up costs were made for different businesses and industries on the basis of type of business and size of plant. Using information gained during the Phase II site visits it was estimated that the decision to institute a special plant-wide clean up would be made on the basis of evidence of major impact of the presence of carbon fibers. Accordingly, it is assumed that an intensive plant cleanup is implemented whenever the plant is shut down due to equipment failures, as described below.

Dislocation Cost

It was assumed that a plant or place of business would be shut down if power is lost, the common module fails, or more than half of the production lines fail. This determination is made for each plant in one SIC-code group at the location. In contrast to Phase I, then, we determined plant closings on a plant-by-plant basis, rather than employing an expected-value algorithm.

The fraction of an industry or business shut down was estimated by computing the employee-weighted fraction of production lost. The method may be expressed as:

$$F.C._{SIC} = \frac{\sum_{Size} (\text{No. of Empl.})_{SIC,\ Size} \times (\text{No. of Plants Shut})_{SIC,\ Size}}{\sum_{Size} (\text{No. of Empl})_{SIC,\ Size} \times (\text{No. of Plants})_{SIC,\ Size}} \qquad (15)$$

The risk assessment model assumes that the impact of a carbon fiber incident on the economy can be measured by the fraction of the local GDP allocated to a particular industry over the period of time that the industry is "down." We assumed that the down time would be of the order of one day. The impact in dollars is then calculated by using this result in the following algorithm:

$$\text{Cost} = K \sum_{SIC} \frac{(\text{Local Payroll})_{SIC}}{(\text{National Payroll})_{SIC}} GDP_{SIC} FC_{SIC} \qquad (16)$$

National-level inputs from the Department of Commerce provide the national payroll broken out by SIC number and the Gross Domestic Product broken out by SIC number. Available data for counties surrounding the particular airport include payroll for each SIC-coded business and industry. The factor K adjusts the result for the fraction of a year the plant remains shut, since the other data is typically annual.

Household Impact

The method used in Phase II is essentially the same as that employed in Phase I. We define the fraction of households in an area that are air conditioned (FAC) and use the methods previously described to estimate the failure probability of vulnerable equipment in air conditioned and non-air conditioned households. The latter calculation includes both the failure and ventilation parameters. If the resulting failure probabilities are $P_{F,AC}$ in the air conditioned household and $P_{F,NAC}$ in the non-air conditioned household, then the

estimated cost to repair all damaged equipments of a particular class at all households is given by:

Repair Cost x Number of Households x Number of Equipments per Household $(P_{F,AC}FAC + P_{F,NAC}(1 - FAC))$

The locations and numbers of residential units were obtained from the Bureau of Census publication, <u>County and City Data Book</u>. Based on the latest experimental evidence our attention was limited to household television and high fidelity equipment, while updated Phase II ventilation data were used.

Geographical Area Specification

As in Phase I, county-based economic data was adopted for computer input; in many cases counties were divided into smaller, homogeneous geographical units. In each case the center of the county or sub-county geographical unit was selected and a representative circle inscribed within the area. The input data set includes the coordinates of the center and the associated radius. The exposure and resulting impact calculations are made at the center and points a distance equal to two-thirds of the radius to the east, west, north, and south of the center. In each case the county-based business/industry sites are uniformly distributed over these five points. The concept is illustrated schematically in Figure 5, as applied to one county for the Washington National Airport risk calculations. In all cases this method was applied to the area around each airport to a distance of 80 km or more.

Aircraft Vulnerability

In Phase I, ORI concluded that key airport operations were relatively invulnerable due to the many designed redundancies in the system. The analysis did not cover the risk to aircraft on the ground at the time of the accident. Because of safety-of-flight, as well as other factors, it was decided that an investigation should be made of the risk to aircraft on the ground, at passenger gates and maintenance locations. This was initiated in Phase II, and focussed on failures of avionics equipment. In a cooperative effort the aircraft manufacturers analyzed data to determine the number of aircraft expected to be at passenger boarding gates and at maintenance locations on the airport by day and night. This was done for the nine airports previously selected as representative (with a bias toward the busier airports). The 1978 data were extrapolated to the 1993 time frame, based on estimated fleet changes. For aircraft at each location a survey was made to provide estimates of the fraction of time each aircraft is in each of several defined ventilation modes. Transfer functions were estimated for each of these ventilation modes, for each of several locations on board small, medium, and large aircraft. The latter data, together with mean-exposure-to-failure values for typical avionics equipment enabled us to estimate the probability of failure of each of several generic classes of avionics equipment on board each aircraft.

A summary of key avionics equipment input data is shown in Table IV. The

aircraft vulnerability module first randomly determines whether the accident occurred during day or night; it then selects the number of each size aircraft at representative gate and maintenance locations. The model aggregates each type of vulnerable equipment over all aircraft in one size range, and randomly determines, based on the input probabilities, the number of equipments in that category in each ventilation mode (transfer function value). The model computes failure probabilities and randomly determines the number of equipments that fail for the computed exterior exposure at each location. With the input repair costs we then determine the total cost. These steps are illustrated in the flow chart appearing as Figure 6.

Costing Summary

At one geographical location the model computes business-industry impact as the sum of costs of equipment repair, facility cleanup, and business disruption. At those locations defined as residential centers the model computes the total cost due to household equipment failures. At the airport the model computes costs required to repair failed avionics equipment. Summary results for each simulated accident present the total of costs in each of these three major categories, obtained by adding the costs over all geographical locations that were affected by the accident.

RESULTS OF AIRPORT SIMULATIONS

Basic Results

The simulation model was run for the nine airports previously studied in Phase I, and listed below:

O'Hare/Chicago

John F. Kennedy/New York City

Washington National Airport/Washington, D.C.

Lambert/St. Louis

LaGuardia/New York City

Logan/Boston

Hartsfield/Atlanta

Miami International/Miami

Philadelphia International/Philadelphia.

Figure 7 illustrates, schematically, the results provided by the simulation of randomly selected accidents. The data for <u>one</u> sample accident is shown in Figure 8. Randomly selected accident and weather parameters are indicated.

In this accident all impacts were limited to Queens County, represented by the circle, where the average exposure was 3.5×10^4 fiber-seconds per cubic meter. Damage to households there totalled $533; business impact was $37,177, of which $5,600 was equipment repair cost and $31,577 was due to business closings.

For each airport the number of samples (replications) was selected so that at least 2500 accidents were simulated. In this section of the paper several examples of the results are presented. The accident results are summarized in Table V. The table shows that the airports near relatively small centers of population tend to have somewhat less costly accidents. The damage to avionics equipment appears to be small at all airports; the largest single impact on avionics in <u>all</u> simulated accidents was $3,910 at Kennedy Airport.

Risk profiles were computed for all of the airports. Examples of several are shown in Figure 9. We first note that O'Hare/Chicago, the nation's busiest airport has a risk profile that shows that the probability of exceeding $10,000 in total CF-related impact is approximately .0004. For St. Louis, the corresponding probability is approximately .0001 (one in 10,000). In comparing the risk profiles shown in Figure 9, it should be noted that O'Hare Airport is a high traffic airport serving a major urban area; Atlanta's airport is also one of the busiest in the nation, while its population concentration is somewhat smaller. St. Louis is characterized as both a low-traffic airport and a relatively low population concentration.

Accuracy/Sensitivity Test Results

Several special analyses were conducted. We computed statistical confidence limits for the risk profiles. In Phase I it was shown that the 95% confidence limits could be expressed as:

$$p \pm 2\sqrt{\frac{p(1-p)}{n}}$$

where p is the computed exceedance probability after simulating n samples. Figure 10 shows the Washington National Airport risk profile with the 95% confidence limits. The confidence limits apply to the purely statistical nature of the simulation, and not to the impact of errors in input data. The results do show that conclusions based on the risk profiles need not be altered because of inherent statistical uncertainty.

An example of sensitivity testing that can be conducted with the ORI risk assessment model is shown in Figure 11. In this figure, two O'Hare/Chicago risk profiles are compared: the best estimate in which the mean amount of composite per aircraft is 2803 kilograms, and a "worst case" in which all aircraft operating at O'Hare are assumed to be large jets with the maximum composite considered for any aircraft, 15,600 kilograms. The comparison shows the significant impact of the increased carbon fiber. Even in this case, however, the probability of exceeding $10,000 in annual damages in only about .005 (five in a thousand).

To test the effect of increasing the sample size the O'Hare/Chicago simulations were run for 22,000 and 44,000 annual samples, resulting in 2537 and 5038 accidents respectively. The outputs are compared in Table VI. The 44,000-sample case indicates that a significantly larger extreme value occurred. The risk profile results are, however, quite similar.

NATIONAL RISK

Method

In order to estimate the total national risk the set of airports for which the individual risk profiles were obtained was used to represent the entire United States. This set of airports accounts for approximately one-third of the nation's commercial traffic. Since they are predominately large, busy airports, this method overestimates the national risk. A random number of accidents is generated for a one-year replication at the national level. Individual accidents are allocated to airports on the basis of that airport's share of the total traffic. Instead of "replaying" the simulation for each airport we saved the individual accident results from the single airport simulations. For each airport that an accident is allocated to, the national model draws an accident at random from that airport's accidents that were simulated previously. Figure 12 is a flow chart for this calculation.

Results

The results of the calculation, using results from the individual airports, and the weighting factors described above, indicate a maximum annual impact for business and industry of $274,000, with a mean of $466. For avionics impact the results are $3,900 and $2, respectively. The national risk profile with the 95% statistical confidence limits is shown in Figure 13. In Figure 14 the Phase I and Phase II results are compared, showing that the new Phase II inputs result in a greatly reduced estimated risk.

SUMMARY AND CONCLUSIONS

ORI, Inc. has developed a versatile generally applicable risk assessment simulation model. Using the best available data - we have assessed the risk associated with the use of carbon fiber composite material in commercial aircraft. Confidence in model-generated results is relatively high, based on examination of the statistical confidence limits, model stability, and sensitivity tests. As a result we conclude that the use of carbon fiber composite material in commercial aircraft structures constitutes a relatively low risk.

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6. K. L. Calder, "A Climatological Model for Multiple Source Urban Air Pollution, Appendix D" to A. D. Buse and J. R. Zimmerman, User's Guide for the Climatological Dispersion Model, EPA-73-024, December 1973.

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TABLE I. - VALUES OF TRANSFER FUNCTION FOR TYPICAL ENCLOSURES

Enclosure Category		Transfer Function
1. Small Equipment Building or Van		.012
2. Medium Equipment Building		.010
3. Large Equipment Building or Factory Building (per floor)		.004
4. Equipment Room in Building (one exterior wall)		.010
5. Utility Room	Filtered	.023
	Non-Filtered	.094
6. Residence	Air Conditioned	.058
	Non-air Conditioned	.004
7. Retail/Wholesale Establishment		.004

TABLE II. - MEAN EXPOSURE TO FAILURE ($\overline{E}$) FOR TYPICAL GENERIC EQUIPMENTS (Fiber-Seconds per Cubic Meter)

Equipment	$\overline{E}$
High-voltage Power Supply	10^8
Interface Unit	10^8
Manual Controller	10^8
Computer ("Standard Size")	10^7
Keyboard-Display Unit	10^8
High-voltage Motor Controller	10^8
Machine Station Servo-Controller	10^8
Sensor	10^7
Power Distribution Panel	10^8
Switchgear	10^8
Auxiliary Generator	10^6

TABLE III. - ASSOCIATION OF PARTICULAR BUILDING TYPES* WITH INDUSTRIAL FACILITY FOR SIC 28 - CHEMICAL AND ALLIED PRODUCTS

Plant Size	POWER MODULE			COMMON MODULE	DISTRIBUTED MODULE
	SW	DIST.	AUX.		
Large	5b	3	5b	4	3
Medium	5b	3	-	-	3
Small	5b	2	-	-	2

* SEE TABLE I

TABLE IV. - AIRCRAFT AVIONICS EQUIPMENT CONFIGURATIONS WITH FAILURE AND COST INPUTS

Aircraft Size	Avionics Equipment ID No.	Number on Aircraft	$\overline{E}$ (Failure Parameter*)	Repair Cost (\$)
Small	1	38	10^8	100
	2	7	1.5×10^7	100
	3	6	10^8	450
	4	2	1.5×10^7	450
	5	1	10^8	300
	6	18	10^8	50
Medium & Large	7	26	1.5×10^7	215
	8	24	10^8	220
	9	153	10^8	175
	10	4	10^8	250
	11	22	10^8	210
	12	43	10^8	385
	13	3	10^8	530
	14	2	10^8	1295
	15	4	10^8	1665

*In fiber-seconds per cubic meter.

TABLE V. - RESULTS FOR SIMULATED ACCIDENTS AT NINE AIRPORTS (1976 DOLLARS)

Airport	Mean			Mean of 10 Worst
	Household	Bus/Ind.	Avionics	
Atlanta	1	70	2	14,238
Boston	2	152	0	35,818
Wash. Nat'l.	5	310	0	62,497
Kennedy	11	199	3	32,544
LaGuardia	11	373	0	56,186
Miami	2	28	1	7,566
Chicago	6	162	1	32,510
Philadelphia	7	192	0	28,971
St. Louis	2	67	0	13,779

NOTE: Approximately 2500 accidents simulated for each airport.

TABLE VI. - 1993 CHICAGO/O'HARE COMPARISON OF DIFFERENT SETS OF SIMULATIONS

	22,000 Samples	44,000 Samples
No. of Accidents	2537	5038
Mean Accident	$147	$166
Worst Accident	$54,000	$110,299
P>$1,000	.000955	.00111
P>$10,000	.000545	.000545

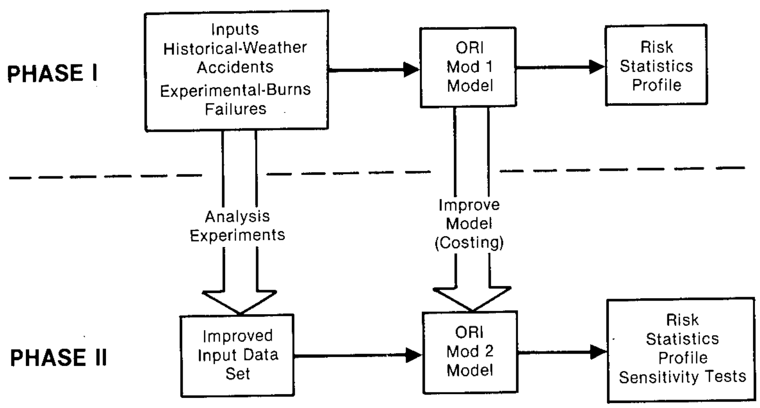

Figure 1.- Conceptual relationship of Phases I and II - ORI carbon fiber risk assessment program.

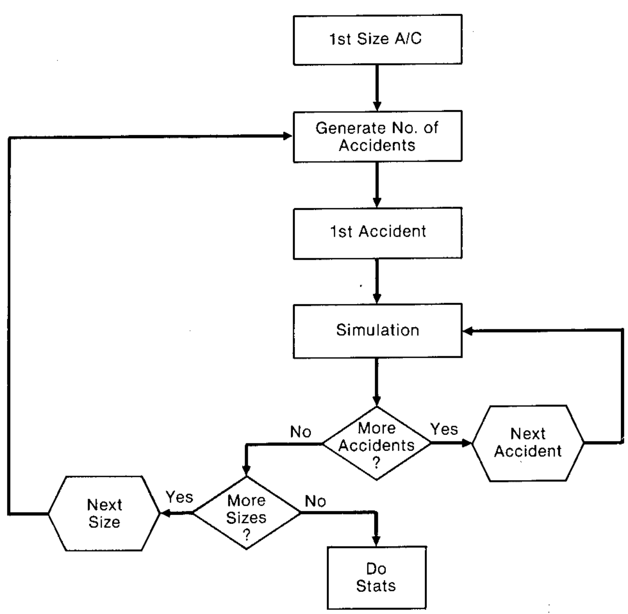

Figure 2.- Flow chart for ORI airport risk model.

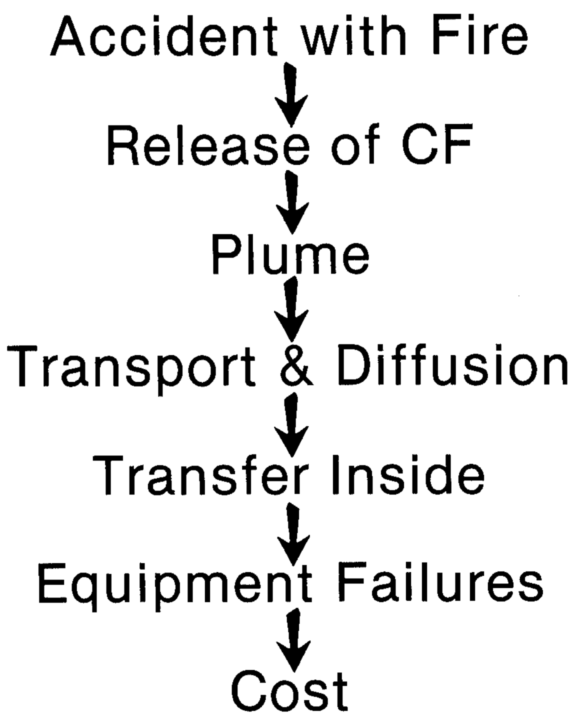

Figure 3.- Events in aircraft accident scenario
replicated in each accident simulation.

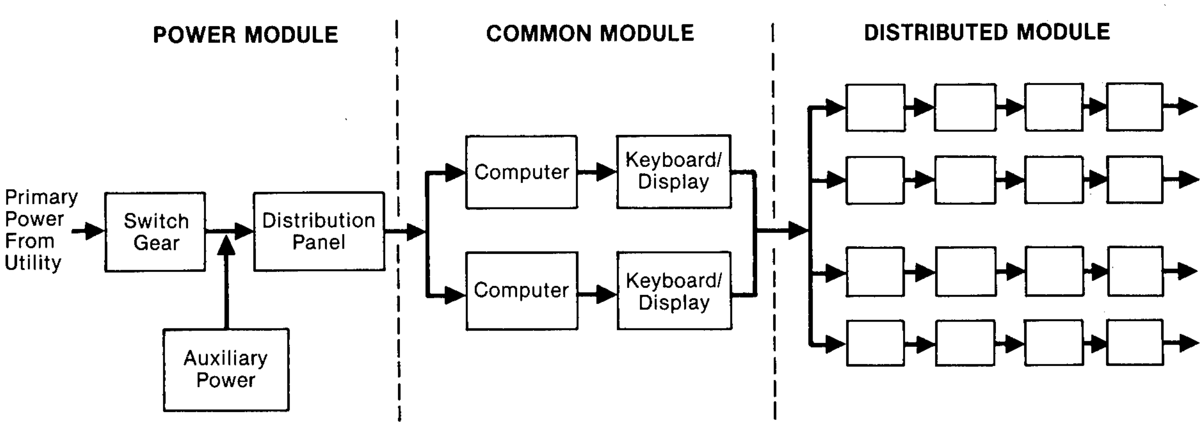

Figure 4.- Schematic electric power flow in typical business/industry facility.

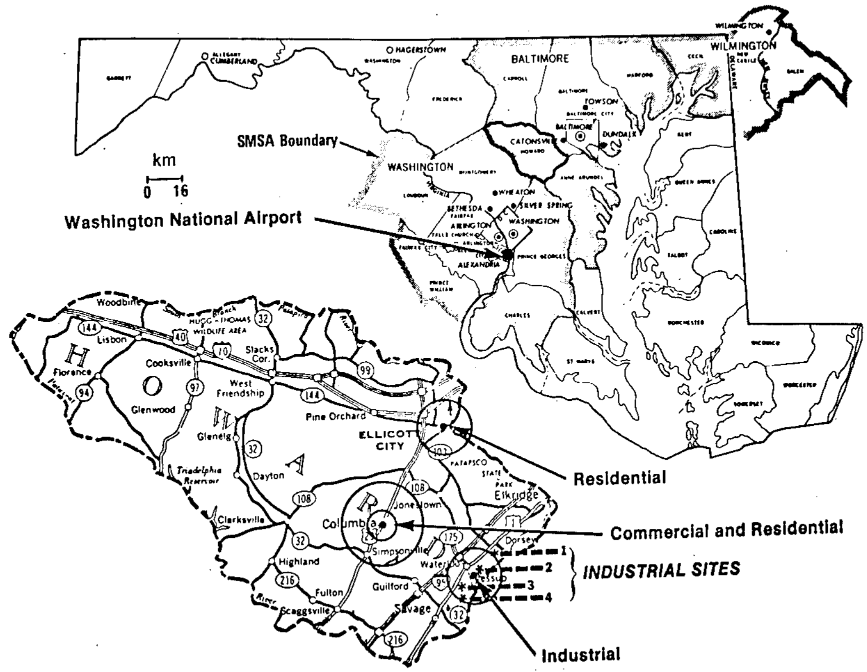

Figure 5.- Definition of areas at risk for Washington National Airport. Howard County, Maryland, outlined in upper map, shown in detail in lower map. Circles represent concentrations of business, industry, and residences.

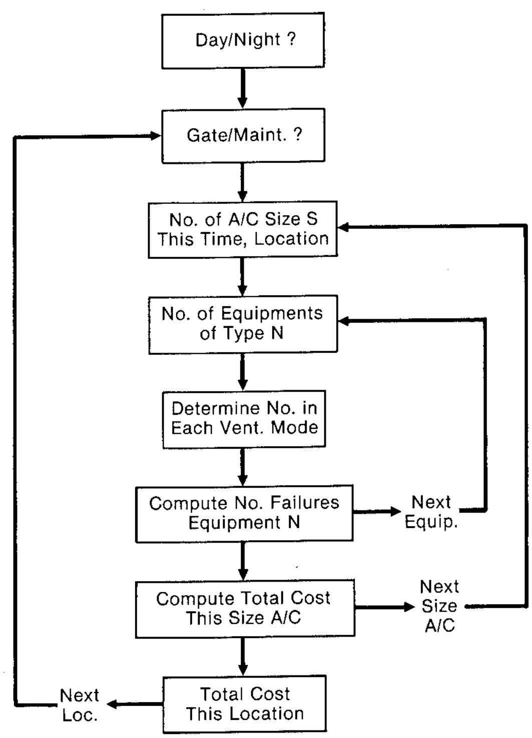

Figure 6.- Flow chart for modeling avionics equipment failures.

SAMPLE NUMBER	ACCIDENT NUMBER	AIRCRAFT CATEGORY	ACCIDENT TYPE	WEATHER	FAILURES	CONSEQUENCES	COSTS

Figure 7.- Schematic illustration of detailed simulation results.

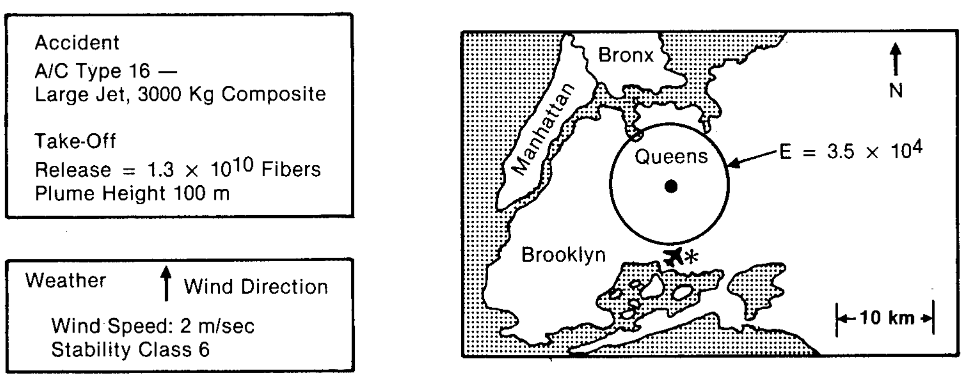

Figure 8.- Factors associated with one randomly generated accident at Kennedy Airport. Airplane indicates airport location; asterisk indicates accident location.

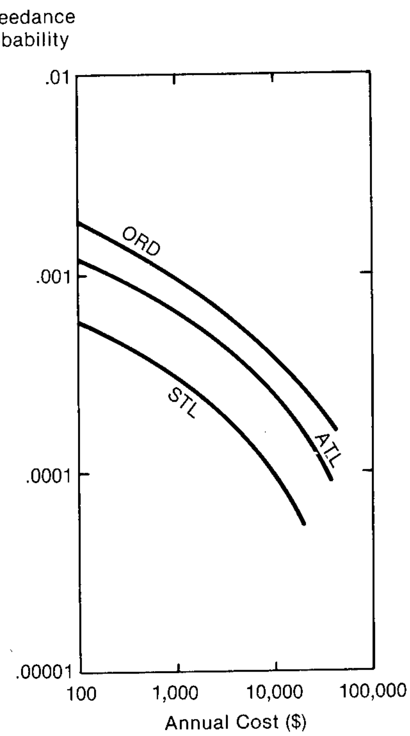

Figure 9.- 1993 risk profiles for selected airports. ORD is O'Hare/Chicago; ATL is Hartsfield/Atlanta; STL is Lambert/St. Louis.

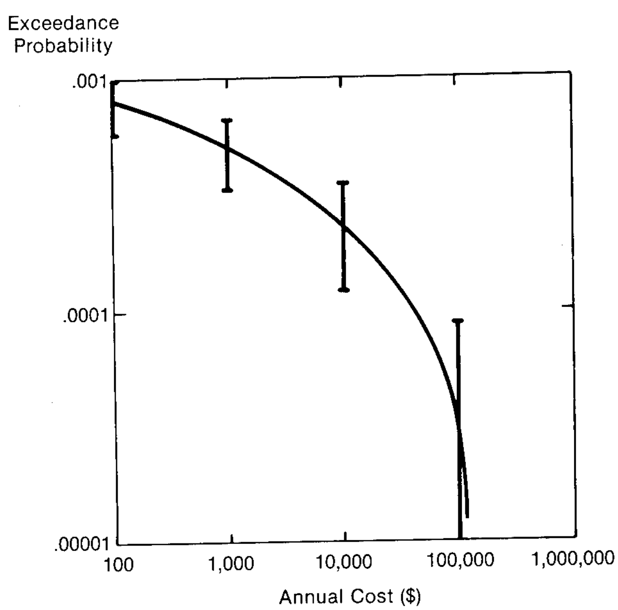

Figure 10.- 1993 risk profile for Washington National Airport with 95 percent statistical confidence limits.

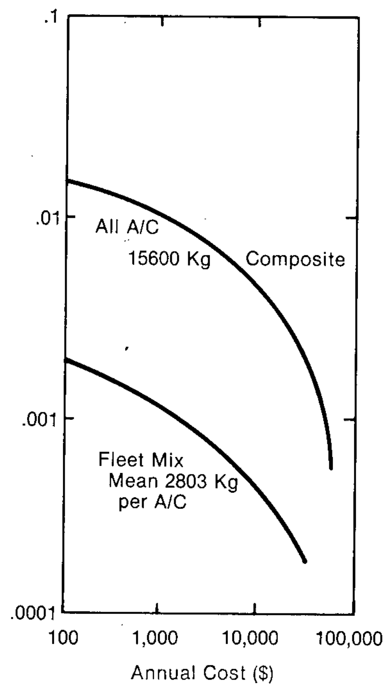

Figure 11.- 1993 risk profiles for O'Hare/Chicago. Comparison of best-estimate with "worst case" in which all aircraft are large jets with maximum carbon fiber.

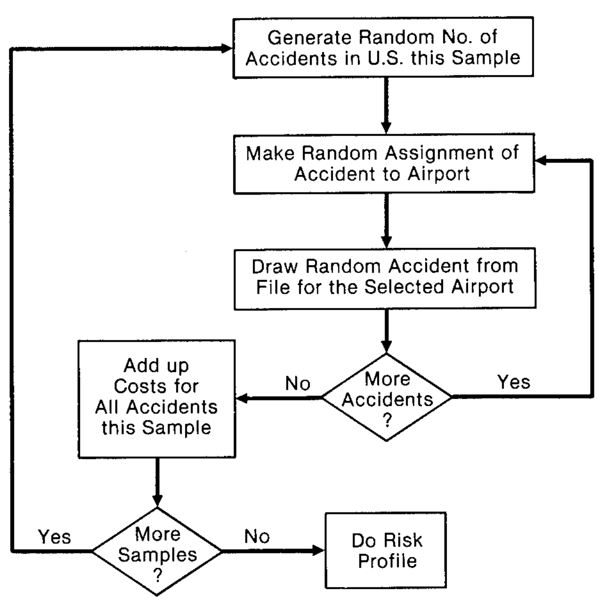

Figure 12.- Flow chart for computing national risk.

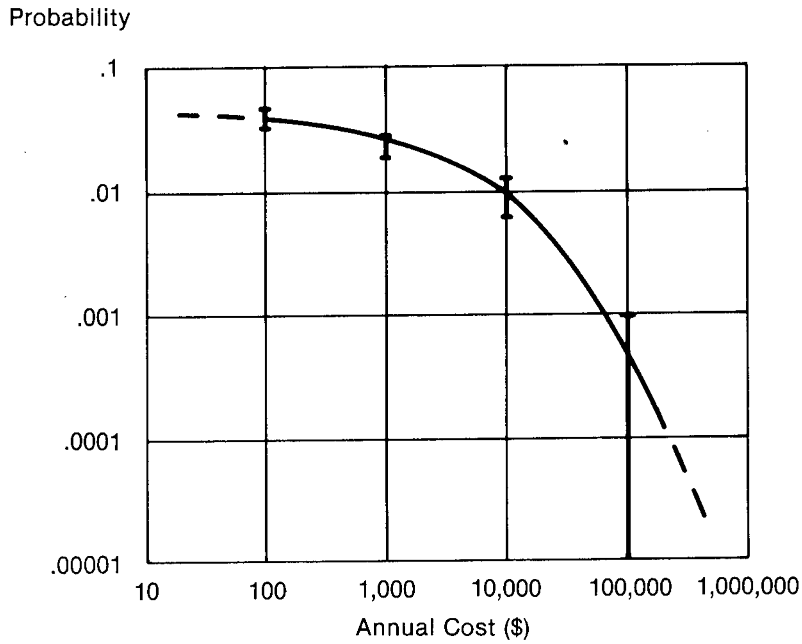

Figure 13.- 1993 national risk profile with 95 percent statistical confidence limits.

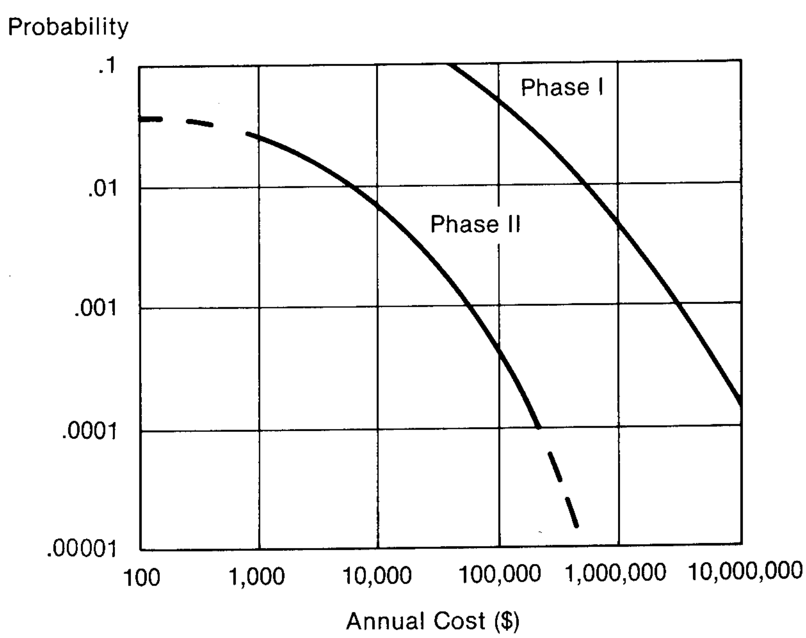

Figure 14.- Comparison of Phase I and II national risk profiles.

ASSESSMENT OF RISK DUE TO THE USE OF CARBON FIBER COMPOSITES IN COMMERCIAL AND GENERAL AVIATION

J. Fiksel, D. Rosenfield and A. Kalelkar
Arthur D. Little, Inc.

INTRODUCTION

Arthur D. Little has been working with NASA for two years in an effort to assess the risks to the nation posed by the potential usage of carbon fiber composites in aviation. Last year at this time we presented the results of a Phase 1 study which estimated the national risk through 1993 due to the potential use of carbon fiber composites in air carrier aircraft. Since then we have performed a number of modifications and revisions to that initial assessment, as shown in Figure 1. The Phase 2 enhancements included refinements in several areas: dispersion models, facility vulnerability analyses, CF release conditions, and risks due to CF usage in general aviation and in surface transportation vehicles. Our presentation is divided into two parts: I will speak on the risks for commercial aviation and Dr. Donald Rosenfield will then discuss our findings for general aviation. The risks due to surface transportation will be addressed by Drs. Hergenrother and Hathaway of the DOT.[1]

COMMERCIAL AVIATION RISK ASSESSMENT

The objectives of the commercial aviation risk assessment are shown in Figure 2. The ultimate objective was the assessment of national risk. To meet this objective, several related objectives were formulated. In order to quantify the amount of carbon fiber that could be found on aircraft, we were required to project the potential usage of carbon fiber composites in commercial aircraft through 1993. In order to estimate the frequency with which such fibers could be released, we were required to investigate the incidence of commercial aircraft accidents with fire and explosion, in terms of both their location and frequency. In order to describe the physical mechanisms whereby fibers could be released and dispersed over the surrounding area, we had to develop dispersion models. A related objective was to estimate the potential economic losses in situations where the accidentally released carbon fibers were able to penetrate buildings and equipment cabinets, creating damaging short circuits. In addition, we were required to explicitly show the uncertainties in the assumptions that entered into the risk analysis, and to test the sensitivity of the risk profile to those input parameters.

The sequence of events that needed to be modeled in order to describe the phenomenon of carbon fiber risk is shown in Figure 3. Air carrier operations will occasionally result in accidental fires and/or explosions. If the aircraft

is carrying carbon fiber composites in the structure, then some of these fibers may be burned away by an intense fire, will rise in the convection plume and will be dispersed over a large area, depending upon the atmospheric conditions and the wind direction. If there are buildings or other facilities located in the path of the carbon fiber cloud, and if these buildings contain electronic equipment which is potentially vulnerable to the fibers, then there is a possibility that they will penetrate these buildings, damage the equipment and thus result in economic losses to the residents or proprietors of these facilities. We will separately address each of the steps involved in this sequence of events and show how we analyzed them.

Carbon Fiber Usage

In order to describe the usage of carbon fiber composites in aircraft, we divided the commercial aircraft into three categories of jets--small, medium and large jets. Each of the jet aircraft produced by the major airframe manufacturers was assigned to one of these classes. We did not consider other classes of aircraft, such as turbo-props, since there is not expected to be a great deal of carbon fiber usage for these type of aircraft. The projections for carbon fiber usage in commercial aircraft are shown in Figure 4. These are based on estimates obtained from the three major U.S. airframe manufacturers, McDonnell Douglas, Lockheed and Boeing. They estimated both the fleet mix, that is the relative numbers of different sizes of aircraft in service in 1993, and the potential usage of carbon fiber composites for each of these classes. As indicated in Figure 4, roughly half of the aircraft in service in 1993 will be large jets, the majority of which will be using carbon fiber composites. The projected weight of actual carbon fibers, including the epoxy binding, ranges from only 11 kg. on some of the small aircraft to as much as 15 600 kg. on some of the large aircraft. For the purposes of the risk analysis we used these estimated ranges to develop a probability distribution for the amount of carbon fiber involved in an aircraft accident.

To characterize air carrier activity within the U.S. as a whole, we focused upon the 26 large hub airports which account for approximately 70% of domestic passenger enplanements. As shown in Figure 5, the balance of the passenger traffic in the U.S. is accounted for by 40 medium hub airports and a large number of small hub airports. Only about 3% of total commercial passenger enplanements occur at airports other than these hub airports designated by the F.A.A. Our approach was to study in detail the traffic patterns and the exposed population in the vicinity of the 26 large hubs and then to extrapolate the resulting risk estimates to the rest of the nation.

Accident Conditions

The typical conditions surrounding a severe fire and/or explosion in the case of an air carrier accident were investigated through use of the National Transportation Safety Board accident and incident statistics for the years 1968-1976. Using their records, we created a data base of aircraft accidents that listed for each accident the phase of operation, the location of the accident, the weather conditions at the time of the accident, the nature of the fire, and

other relevant details. This data base was augmented with the help of the airframe manufacturers who provided additional data on accident characteristics, such as fire duration, that would affect carbon fiber release conditions. We then utilized these data to determine the distribution of possible accident characteristics. We found that almost half of the severe accidents involving fire occurred during the landing phase. As shown in Figure 6, the take-off phase accounts for one-quarter of these accidents, with the remainder being distributed in either the static/taxi or cruise phase. Cruise accidents were dealt with through a separate analysis since the location of these accidents is essentially random. However, the static, take-off or landing accidents were all associated with specific airport locations.

From an analysis of the location of accidents relative to airport runways, we found that over 80% of accidents occur within 10 kilometers of the airport, and in fact 60% of accidents occur at the airport. We also investigated the angle between the accident location and the line of the runway to establish more precisely the potential locations of such accidents.

Historically, there have been about 3.8 accidents per year involving jet air carriers. Although air carrier operations are gradually increasing in number, the accident frequency appears to be relatively constant from year to year. Therefore, we did not project any increase in accidents through 1993. Based on the expected fraction of the air carrier fleet that would be carrying carbon fiber in 1993, the projected frequency of incidents involving fire on aircraft carrying composites of carbon fibers would be approximately 2.7 per year in 1993.

Release and Dispersion

There are two different types of scenarios that describe possible carbon fiber release situations in the aftermath of an air carrier incident. One of them is a simple fire plume in which the fibers are carried aloft by the plume and then dispersed. The second is the fire and explosion case in which there is a sudden rapid conflagration of fuel resembling an explosion, in which much more rapid burning of composite and a sudden release of fibers can take place over a short period of time. Based on the 92 accident data base compiled by the airframe manufacturers, we estimated conservatively that at most 5% of air carrier accidents would result in explosive release of carbon fibers of the type described.

The two dispersion models corresponding to the two accident and carbon fiber release scenarios are shown graphically in Figure 7. In the fire and explosion case, we consider only those accidents in which there was a delayed explosion preceded by a period of burn during which the epoxy or resin surrounding the fibers would be burned away. This would expose the carbon fibers to an agitation by the force of the conflagration and thus would hypothetically result in a larger number of single fibers released. This scenario was modeled as an instantaneous release in the form of a cloud at a height of 10 meters above the site of the accident. In the fire plume model, rather than having an instantaneous release, we have a continuous release of fibers over the period that the aircraft burns. The carbon fiber plume rises until it meets the inversion layer

and then is tilted or reflected back toward the ground. The direction and velocity of the wind determine the exposure contour over which carbon fibers will be deposited.

The extent of dispersion of carbon fibers from a burning aircraft and the level of resulting exposures to the surrounding area are greatly influenced by the release conditions at the time of the accident. Release conditions include the weather conditions, such as atmospheric stability class, wind velocity and wind direction. These were examined at each of the 26 major airports with the help of NOAA statistics. However, it was more difficult to estimate the release conditions associated with the duration and the intensity of the fire. With the help of the 92 accident data base compiled by the airframe manufacturers we were able to develop distributions for several of the important release variables, as shown in Figure 8. These included the time of burn--that is, the duration over which the fire lasted, the percent of fuel burned, and the percent of carbon fiber involved. Our approach to estimating CF involvement is described below. The degree of carbon fiber involvement was correlated with both the duration of the fire and the percent of fuel burned. Roughly speaking, the greater the amount of fuel burned, the longer the duration of the burn, and the greater the potential carbon fiber involvement. In addition, the amount of fuel on board was estimated for different phases of operation and different aircraft size categories, and the amount of carbon fibers on board was estimated for the three size classes of aircraft. This allowed calculation of the actual amount of fuel burned and the actual amount of carbon fiber involved.

Even though an aircraft may be carrying over 15 000 kg. of CF composite, the amount of carbon fibers that could be released in a fire is significantly less, partly because of the fact that not all the carbon fibers can be released as single fibers in a burn, and partly because the entire aircraft structure will not necessarily be involved in the fire.

Based on experimental findings, which were described by Dr. Vernon Bell,[2] it is estimated that not more than 1% of the carbon fibers would be released in most fire plumes, and that not more than 2.5% would be released in most fire and explosion scenarios. These are conservative estimates using the best judgment and interpretation of the experiments conducted by NASA and other groups on burning composite materials.

To examine structure involvement, we used the results of an analysis by the airframe manufacturers, who estimated the amount of structure that could be involved in a fire for various components of their aircraft. Using the data base of 92 fire incidents, they estimated the percent of each component that was involved in the fire, thus creating a distribution of potential structural involvement. As shown in Figure 9, we combined the structural damage estimates with the projected usage of carbon fibers by component (also developed by the airframe manufacturers) to produce estimates of the potential carbon fiber involvement in air carrier fires. The range of involvement varied from zero, reflecting a fire which did not damage any of the structure containing carbon fibers, to 100% involvement in which all portions of the aircraft containing CF were completely involved in the fire. Our median estimates of carbon fiber involvement were 45% for small jets, 69% for medium jets, and 64% for large jets. This variation is due largely to the different levels of CF usage in the different aircraft size classes.

Exposure Contours and Demographics

A simplified illustration of exposure contours is shown in Figure 10. Note that the aircraft runway here has not been drawn to scale. Assuming that an incident is located at some distance from the runway, the carbon fiber cloud will move in the direction of the wind and may travel for distances of as much as 80 kilometers. The exposure is a measure of concentration over time, and as we move farther from the incident location, the exposures to carbon fibers will tend to decrease. Figure 10 shows three exposure contours corresponding to exposures of 10^5, 10^4, and 10^3 fiber-sec./m^3. In our simulation approach we applied the appropriate dispersion model to each simulated accident and calculated the resulting exposures at various points surrounding the incident location. The physical mechanisms underlying carbon fiber dispersion have been described thoroughly by Dr. Wolf Elber.[3]

In order to assess the potential damage due to such a release, we performed a demographic and facility analysis for each of the 26 major airports. Upon each of these airports we superimposed a circular grid as shown in Figure 11, which divided the area surrounding the airport into 40 geographic sectors of varying sizes. The edge of the outside sectors was 80 kilometers from the airport center. Using the results of the selected dispersion model for each simulated accident, we calculated an exposure distribution within each of these sectors. That is, we estimated the proportion of each sector that experienced an exposure of 10^8, 10^9, etc. We also enumerated the facilities, residences and other structures containing potentially vulnerable electronic equipment within each of these sectors, using census data and other sources. The categories of vulnerable facilities that were considered are shown in Figure 12. They included households, or private residences; manufacturers of electronic equipment, computers and aerospace equipment, as well as manufacturers of non-electronic equipment whose production control systems might be vulnerable; transportation, including aircraft and air traffic controls, mass transit, and railways; communication facilities including telephone, radio, TV and micro-wave installations, and post offices, in particular the optical character reading equipment; and fire and police communications. In terms of business services, we included in our enumeration financial and insurance services, software and electronic data processing services, as well as hospitals. We also enumerated retail outlets and office buildings, which could contain varying amounts of electronic equipment. Because of the widespread use of electronics in contemporary society, and because of the tremendous growth rate envisioned for electronics in 1993, it was necessary in this risk analysis to consider almost every category of private or public building as being potentially vulnerable. We examined the properties of such buildings in terms of penetration, ventilation and filtration and concluded that some of them were not very vulnerable, for example, hospitals. The results of our facility site visits and vulnerability analysis have been presented by Ansel Butterfield.[4]

Monte Carlo Simulation

I have described the various elements of our analysis which provide

the necessary inputs for a Monte Carlo simulation. These data inputs included the accident characteristics, the release conditions, the dispersion model, and the characteristics of vulnerable facilities. Once these elements had been assembled, we performed a Monte Carlo simulation of potential aircraft accidents at each of the 26 large hub airports. We used the Monte Carlo method to develop an individual risk profile for each airport, and then these risk profiles were combined into a national risk profile. (A risk profile is a graph indicating the probability of exceeding various levels of dollar loss.) Figure 13 shows the Monte Carlo procedure for an individual airport. Each point at which a question mark is shown denotes a random draw from an input distribution. These distributions were developed through the analyses discussed previously.

The Monte Carlo procedure works in the following manner: It simulates a large number of accidents, on the order of hundreds or thousands of accidents, and for each one draws from probability distributions a set of conditions for that accident. By repeating the simulation many times, we show the full range of possible accident types and thus develop a distribution of the potential accident results. As shown in Figure 13, the aircraft and incident details, such as the size of the plane and the phase of the operation, are randomly drawn, and these in turn influence the probable accident location, the likelihood of a delayed explosion, and the assumed release conditions.

If an explosion does occur, which happens about 5% of the time, then the fire and explosion model is selected, whereas if it does not occur, the fire plume model is selected to compute exposures. The weather conditions such as stability class and wind velocity are drawn from weather distributions for the particular airport in question, and these together with the release conditions determine the exposures resulting from the dispersion model. These exposures are then calculated at a large number of points within the 40-sector grid and an exposure distribution is found for each sector. From this exposure distribution we use the penetration and vulnerability characteristics of the facilities exposed, and an economic analysis model which estimates the economic losses resulting for each affected facility. The losses are then summed to determine the total economic losses resulting from the simulated accident. Once this is complete, the computer returns and simulates another accident, drawing a new set of aircraft/incident details. This procedure was repeated iteratively until enough samples had been taken to get a reasonably accurate distribution of the economic losses resulting from an accident. In this way we developed 26 individual risk profiles for the large hub airports.

An example of the outcome of a typical computer simulation is shown in Figure 14. In this case, the computer generated a hypothetical accident at La Guardia airport, relatively close to the center of a runway. The aircraft involved was a medium jet in a static or taxi phase, which somehow caught fire. About 8500 kg. of fuel were burned over a period of more than thirty minutes, releasing 22 kg. of carbon fibers. There was also a delayed explosion during the burn. Based upon the randomly drawn weather conditions, the CF cloud moved westward, toward New York City, creating exposures as high as 10^8 fiber-seconds per cubic meter at the airport, and 10^7 fiber-sec./m^3 within 3 km. of the airport. The resulting losses due to equipment failures amounted to a total of \$178, of which households accounted for \$66. By performing hundreds of iterations like this one, the computer generated a risk profile for La Guardia airport.

The next task was to derive the national risk profile. This was done by combining the individual risk profiles with information concerning potential losses due to cruise accidents and accidents at airports other than the 26 considered.

Risk Profile Development

We developed two kinds of national risk profiles in this analysis. One of them was the risk profile for a single incident, which gave the distribution of dollar losses resulting from any one air carrier accident. This was derived by taking a weighted mixture of the individual airport risk profiles for a single incident, weighted by the frequency of incidents at each airport. This procedure is shown in Figure 15. The second type of national risk profile derived was the national annual risk profile which showed the distribution of total losses due to accidents involving carbon fibers. This annual risk profile incorporates the possibility of one, two, three or more accidents involving carbon fiber release during any given year. To derive the annual risk profile we used the national risk profile for a single incident and performed a convolution procedure based on the annual frequency of such accidents.

Before proceeding to the results of the risk analysis, it is important to note the major assumptions that entered into this analysis. The most important assumptions are listed in Figure 16. First, atmospheric conditions are assumed to remain constant during the dispersion of the carbon fiber cloud. This is a somewhat unrealistic assumption since weather conditions are constantly changing, and a cloud moving at a rate of a few kilometers per hour could take as much as a day to cover 80 kilometers. However, it would be too complex to simulate different atmospheric conditions in different geographic sectors, and therefore this assumption was made. The assumption is not expected to introduce any bias into the risk analysis since the variation of atmospheric conditions will sometimes increase and sometimes decrease the resulting exposures. We also assumed that there was no precipitation, which is a conservative assumption since if precipitation does occur it may wash out some of the fibers, resulting in lower airborne exposures on the ground. It was found that there was a high likelihood of rain or other forms of precipitation being associated with an aircraft accident, since many of the accidents in the historical data base occurred in IFR, or instrument flight rules weather. The second major assumption is that for a given facility category all facilities are equal in size, equipment inventory, and financial characteristics. Again this is a necessary assumption due to the enormous volume of data that would have to be processed in order to identify all the different sizes or scales of facilities that do exist. Instead, we took the average case, based upon regional statistics for each facility category, and attempted to model the typical vulnerable facility. The variation in facility characteristics would introduce a little more variation into the risk profile but should not affect the results too greatly because of the large number of facilities involved that would tend to average each other out. The third major assumption is that all equipment is activated and that failures occur immediately after exposure. This assumes, first of all, that equipment which is exposed is in an activated state and is vulnerable to the fibers at the time of exposure. Since some fraction of the eletronic equipment exposed will not be activated,

this tends to be a conservative assumption. On the other hand, there is a phenomenon of post-exposure vulnerability, in which fibers that are deposited upon equipment do not cause a problem immediately but will affect the equipment when it is turned on at a later date. This phenomenon was not modeled explicitly, but it is taken into account by assuming continuous activation and failures immediately after exposure.

The annual risk profile for economic losses due to air carrier fires involving carbon fibers is shown in Figure 17. The horizontal axis shows the total economic losses in dollars as a result of carbon fiber accidents during a given year. The vertical axis shows the annual probability of exceeding each dollar loss value. For example, an annual loss of approximately one thousand dollars would be exceeded with a probability of 10^{-1}, in other words once every ten years. An annual loss of ten thousand dollars would be exceeded about once every three hundred years. The expected annual losses due to CF released from air carrier fires in 1993 is about \$470. This includes only those losses incurred by failures of equipment in the civilian sector.

Discussion of Results

The confidence bounds on the risk profile show the sensitivity of the risk estimates to variations in the input parameters. These confidence bounds are based upon several different sources of uncertainty: the statistical error due to the simulation method, the statistical error in estimation of accident frequency, and the modeling errors due to uncertainty about input parameters. The former two sources of uncertainty were judged to contribute less than an order of magnitude to the confidence bound at the high-loss extreme, and considerably less than that at average loss values. The confidence bounds are wider at high loss values because the simulation may not turn up an extremely unlikely high-loss event even among thousands of simulated events.

To estimate the modeling errors, we performed a sensitivity analysis by varying several of the key input parameters. The results are shown in Figure 18. This analysis was run on the individual airport risk profile which had the highest mean loss of the 26 hubs, namely Detroit. Of the three parameters tested, the largest increase in risk was obtained by setting the composite on the aircraft at its highest possible value, 15 652 kg. This increased the mean loss per incident by a factor of about 7, and increased the standard deviation and maximum value of the losses by a factor of about 4.5. Restricting the simulation model to only explosive releases increased these statistics by a factor of 2 or 3, while setting the atmospheric stability class to E (moderately stable weather) increased the loss distribution only slightly. The two latter conditions are those which tend to result in highest exposures downwind of the release point. We concluded that modeling errors contributed less than an order of magnitude to the uncertainty of the risk profile.

As a final verification of the simulation results, we compared the national conditional profile for dollar losses per incident against a risk profile obtained through an alternative analytic approach. The latter approach, which is based upon a Poisson model of equipment failures, will be described by Dr.

Rosenfield in the context of the general aviation risk assessment. As shown in Figure 19, the two methods agreed fairly well, with their mean values differing by a factor of less than 3. The simulation indicated an average loss of $172 per incident, while the Poisson method resulted in an average loss of $472 per incident.

GENERAL AVIATION RISK ASSESSMENT

This section reports on the investigation of the effects of carbon fiber usage in general aviation aircraft. The objective of this analysis was to assess the national risk through 1993 in terms of economic losses and to determine the sensitivity of the risk assessment to uncertainties in the input data. In formulating this objective, we identified as sub-objectives the projection of potential usage of carbon fiber composites in general aviation aircraft through 1993 and the investigation of fire accidents in general aviation within the U.S. The risk assessment thus involved forecasting future carbon fiber usage, development of an accident model for general aviation aircraft, analysis of the possible release amounts in general aviation accidents, and assessment of the economic consequences of a given release. These objectives are summarized in Figure 20.

Methodology Overview

The methodology utilized for the general aviation risk assessment was quite different from that utilized for commercial aviation. The major issues involved in selecting a methodology are summarized in Figure 21. The simulation model is more appropriate for large releases which will result in large numbers of failures, and allows detailed identification of the geographic distribution of facilities as well as of the different possible accident and release conditions. As noted previously, the simulation approach results in statistical uncertainty at the high-loss tail of the risk profile. In the case of general aviation, the number of failures per incident was expected to be extremely small, and the dominant variation in economic losses appeared to be caused by the random failure process rather than by the variations in physical conditions. Furthermore, there were insufficient data available to allow a detailed modeling of release and dispersion scenarios.

For these reasons, an analytic methodology was developed to synthesize the accident model and carbon fiber usage forecast for assessment of the economic consequences of accidents. This methodology is shown in Figure 22. There were two key parameters influencing the economic consequences of accidents. The first was the amount of fibers released in an accident. By examining the different types of general aviation aircraft and their accident statistics, a distribution of amounts of carbon fibers potentially released in accidents was developed. The second key parameter was the density of facilities near the location of an accident. Thus, an important aspect of the accident model was a quantitative description of the distribution of facility densities. The 3,000 counties in the United States were chosen as a basis for estimating facility density, and hence a methodology was developed to apportion accidents

to the various counties. After a range of county and release amounts was developed, the distribution of failures given an aviation accident was determined. A Poisson probability model was developed for this purpose and a computer program was utilized to tabulate failure probabilities as a function of the amount released and the county, and to aggregate these into a national risk profile of dollar losses. Based on the distribution of the number of equipment failures per accident, the statistics of dollar losses per accident, and the number of accidents per year, expressions were developed for the mean and standard deviation of a dollar loss per year. From these statistics, approximations and bounds were developed for the probability distribution of annual economic losses.

Before examining the details of this methodology it is important to understand the theoretical basis of the Poisson approach, as depicted in Figure 23. For a given release scenario and equipment type, the number of equipment failures may be approximated by a Poisson distribution with mean N_O. The mean number of failures is given by integrating the equipment density over the area in question and multiplying by the equipment failure probability, which is nearly linear in E for low values of the exposure E. Now, provided the amount released is held constant, we can aggregate over many release scenarios, and show that the average N_O is proportional to the surface integral S of the exposure, which in turn may be shown to depend only on the amount released. Thus an expression is obtained for the mean number of failures per incident in terms of just the average facility density, the amount of CF released, and the equipment vulnerability. This enables us to assess the risk without requiring detailed data on accident conditions or geographic locations.

Steps in Risk Analysis

The first step in the risk assessment procedure was the development of a forecast of the usage of carbon fibers in general aviation aircraft and determination of the potential amounts released in accidents. Figure 24 presents a table summarizing our projections. For the purposes of this analysis, we identified three classes of general aviation aircraft. These were: single-reciprocating-engine craft; multi-engine and jet aircraft; and helicopters, non-fixed wing and non-powered craft. Of the latter category, helicopters represent nearly all of the accidents historically. The annual growth rates for the number of aircraft in each of these categories are 6.3%, 4.8%, and 8.6%, respectively. Thus, the number of craft in 1993 will be 321,000; 72,500; 25,000; respectively. It is estimated that about 25% of the general aviation fleet will be carrying carbon fiber composites in 1993. Of these craft, helicopters will be using the largest amount of carbon fiber composites, about 54.5 kilograms, and the other classes of aircraft will be using substantially less than this. In a fire accident, any release up to 2% of the weight of the composite is possible. Based on NASA estimates, a one-half percent release was assumed for the case of substantial damage. Thus, the maximum conceivable carbon fiber release in a general aviation accident is about 1.1 kilograms.

The accident model addressed three issues:

- An allocation of accidents to the 3,000 counties in the nation

- A determination of the number of fire accidents per year

- A determination of the conditional scenario probabilities. A scenario consisted of an aircraft type, damage level, and type of accident (cruise or on airport).

As shown in Figure 25, accidents taking place on or near airport were allocated to the various counties on the basis of total operations. Cruise accidents were estimated to be proportional to the general aviation miles or hours flown in a given county. In determining probabilities based on these criteria, there were two problems encountered. The first problem was that only 30% of general aviation operations could be attributed to given counties, based on FAA statistics. The remaining operations were allocated to the counties in each state according to population. The second problem was that there were no data available on air mileage or flight hours within each county. Air hours were estimated for each county by taking a weighted average of the local and itinerant operations attributable to that county. Weighting factors were based on the average length of time of itinerant and local operations. There was an implicit assumption that each operation takes place wholly within the county or counties corresponding to the operation's origin and destination.

The accident probability estimates used in the risk assessment are shown in Figure 26. According to the National Transportation Safety Board accident statistics from 1968 to 1976, there are approximately 340 general aviation fire accidents per year. Although the number of operations is increasing, the accident rate is decreasing and the number of accidents per year has remained approximately constant. On this basis we assumed that there will be about 340 general aviation fire accidents in 1993. Of these, based on a 25% incidence of carbon fiber composites in the general aviation fleet, we estimate that there will be 85 fire accidents for carbon fiber-carrying general aviation aircraft in 1993. Air taxi and commuter operations would raise this to 88 accidents in 1993. This figure was used in the subsequent analysis.

Figure 26 also presents the conditional probabilities of different accident types given that an accident occurs. These scenario probabilities are based on the 3058 accidents that occurred from 1968 to 1976. They represent the relative frequencies of aircraft and accident categories adjusted to account for the growth rates of different aircraft classes. Thus, for example, because the helicopter category is characterized by a higher growth rate, the scenario probabilities for helicopter accidents are slightly higher than the relative frequency of helicopter accidents from 1968 through 1976.

After having determined the county and release amount probabilities, we used a computer program to tabulate the probability distribution of the number of failures per accident. The basis of the program was the Poisson model for the number of failures given a density of facilities and amounts released. For general aviation accidents the expected number of failures per accident is substantially less than one as shown by the distribution in Figure 27. The average value is 0.022 although the average would be larger for certain combinations of county and release amount. For this order of magnitude nearly all of the variation in number of failures per accident is due to the random nature of failures, rather than the release conditions such as wind direction and fire intensity.

As mentioned earlier, the expected number of equipment failures is thus proportional to the density of facilities and the amount of carbon fibers released, and inversely proportional to the mean outside exposure to failure for each equipment class. Furthermore, the number of failures can be described by a Poisson probability distribution with the parameter equal to the expectation. The important aspect of the Poisson model is that it eliminates the need for analysis of release conditions other than total amounts released.

Risk Profile Generation

Because of the large number of equipment categories, counties, and amounts released, a computer program was necessary to tabulate the various parameters of the Poisson distributions. The procedural flow of the computer program is depicted in Figure 28. For each combination of amount of carbon fibers released and county location, an expectation is determined together with a probability distribution based on this expectation. From the county location probabilities and the amount released probabilities a national conditional distribution can be developed for the number of failures given an accident. Based on the statistics of economic losses for each given equipment category, the relative Poisson parameters for the various equipment categories, and an annual accident frequency, the mean and standard deviation of dollar loss were computed for a single accident and for total annual loss. We found that for general aviation accidents the mean annual loss was estimated to be $253, as shown in Figure 29. The standard deviation was $1067.

For losses near the mean value a normal distribution is a reasonable approximation. For high dollar losses, however, it is necessary to develop statistical upper bounds based on the mean and standard deviation of annual loss. From standard statistical results, it is known that the probability of a random event exceeding a given number of standard deviations above the mean is inversely proportional to the square of that number of standard deviations. Thus, for example, the probability of a random event exceeding 100 standard deviations above the mean is no more than $1/100^2$ or 10^{-4}. Based on this inequality, we developed the upper bounds on the distribution for annual dollar loss given in Figure 29. Using these bounds and a normal approximation near the center of the distribution, the risk profile depicted in Figure 30 was developed. It can be seen that the chances of exceeding losses of about $1 million are less than 10^{-6}, or once every million years.

Discussion of Results

From this analysis we may conclude that it is highly unlikely that there can be a substantial dollar loss due to carbon fiber releases in general aviation accidents. To check the result, the sensitivity of the annual risk was analyzed with respect to uncertainties in the input data, as shown in Figure 31. If amounts released have been underestimated by a given factor or equipment vulnerabilities have been overestimated by a given factor, then there is a direct proportional effect on the probability factors for the annual loss

distribution. That is, the probabilities are increased by the same factor. As an example, if the carbon fiber releases go up by a factor of 10 or the vulnerability decreases by a factor of 10 the probabilities also go up by a factor of 10. Thus, the probability of exceeding 1 million dollars in losses in a given year goes from 10^{-6} to 10^{-5}. Such changes still represent low probabilities of substantial losses.

In conclusion, it appears that the expected annual risks to the U.S. due to the potential use of carbon fiber composites through 1993 are less than a thousand dollars per year, and that the chances of national losses reaching significant levels are extremely small. However, it should be noted that this risk assessment has addressed only dollar losses due to equipment failure in the civilian sector, and does not quantify other categories of risk such as costs of protection or cleanup of equipment, CF releases from non-aviation sources such as incineration of sporting goods, possible environmental damage by carbon fibers, or impacts upon military operations.

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4. Butterfield, Ansel J.: Surveys of Facilities for the Potential Effects From the Fallout of Airborne Graphite Fibers. Assessment of Carbon Fiber Electrical Effects. NASA CP-2119, 1980. (Paper 7 of this compilation.)

- Refinement of dispersion models to provide more accurate exposure estimates
- Detailed field visits and vulnerability analyses for specific facility categories
- Development of more accurate estimates for aircraft structural damage and CF release conditions
- Incorporation of improved forecasts to 1993 jet aircraft fleet mix and carbon fiber usage
- Improvement of confidence in risk profile through detailed sensitivity analyses and the development of an alternate methodology
- Extension of risk analysis to include CF usage in
  - General aviation
  - Surface transportation vehicles

Figure 1.- Phase 2 enhancement to carbon fiber risk assessment.

MAJOR OBJECTIVE:

- Develop a national risk profile for total annual losses due to CF usage through 1993

SUB-OBJECTIVES:

- Project potential usage of CF composites through 1993
- Investigate incidence of commercial aircraft fires within the U.S.
- Model the potential release and dispersion of carbon fibers from a fire
- Estimate potential economic losses due to CF damaging electronic equipment
- Show explicitly uncertainties and assumptions in the risk assessment
- Examine sensitivity of the risk profile to changes in the input parameters

Figure 2.- Commercial aviation risk assessment.

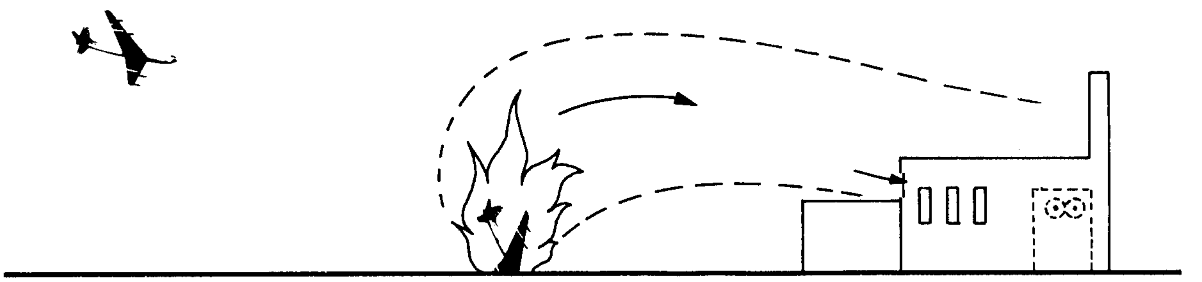


Figure 3.- Sequence of events to be modelled.

	Size of Jet			
	Small	Medium	Large	TOTAL
Number of Aircraft in Service	560	780	1399	2739
Number of Aircraft Using CF Composites	100	754	1127	1981
Composite Mass per Aircraft (KG):				
Min.	11	215	155	
Max.	183	3787	15,652	

Figure 4.- Projected 1993 usage of carbon fiber composites in commercial aircraft (based on estimates of airframe manufacturers).

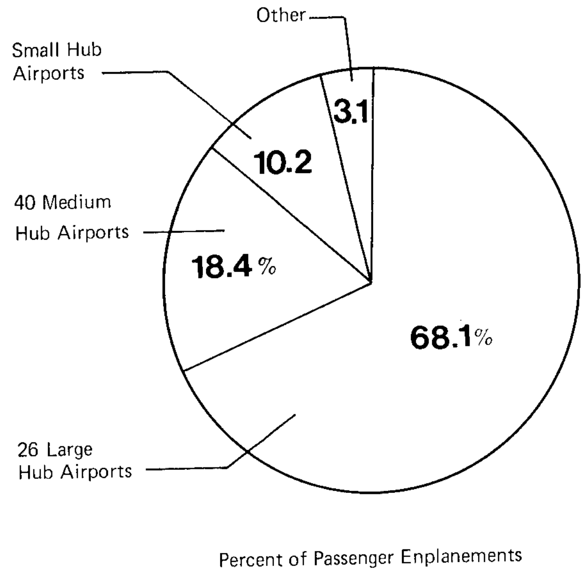


Figure 5.- Distribution of air carrier enplanements (source: 1977 airport activity statistics - FAA, CAB).

- Phase of Operation:

Cruise	16%
Static/Taxi	13%
Take-off	25%
Landing	46%

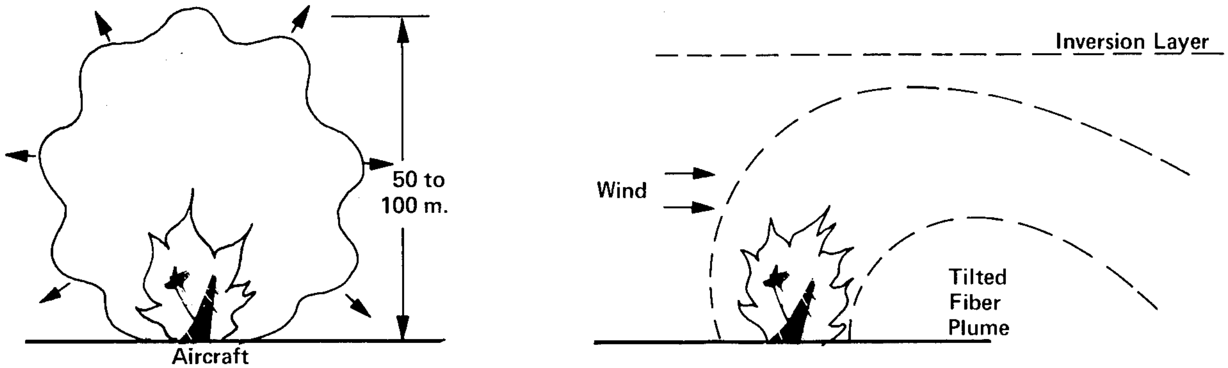
- Location relative to runway:

At Airport	61%
Within 1 KM	67%
Within 10 KM	83%

- Historical Frequency: 3.8 per Year

  Projected Frequency of
  Incidents in 1993
  Involving CF: 2.7 per year

Figure 6.- Domestic air carrier incidents with severe fire and/or explosion (source: NTSB accident/incident statistics, 1968-1976).



1. Fire followed by a delayed explosion (instantaneous release model)

2. Fire Plume Model

Figure 7.- Dispersion models.

- From 92 accident data base:
  - Time of burn
  - Percent of fuel burned
  - Percent of CF involved

  } Correlated variables

- Amount of fuel on board
  Amount of CF on board

  } Depend on phase and size category

- Type of release:

Fire plume	95%
Fire and explosion	5%

- Percent of burning CF
  Released as single fibers:

Fire plume	1%
Fire and explosion	2-½%

Figure 8.- Assumed release conditions for aircraft fires involving carbon fiber.

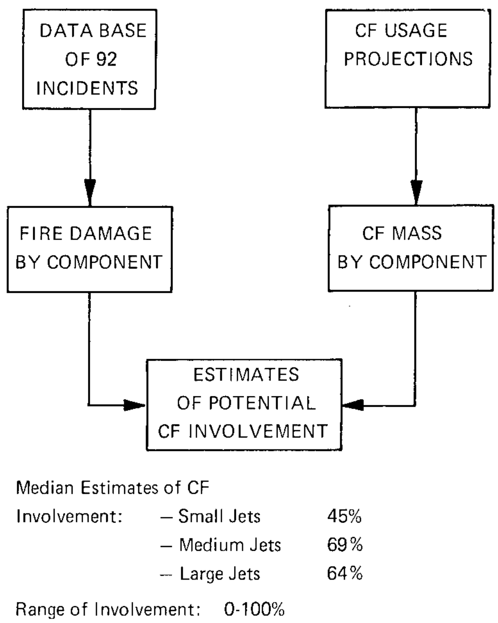


Figure 9.- Potential carbon fiber involvement in air carrier fires: analysis by aircraft components.

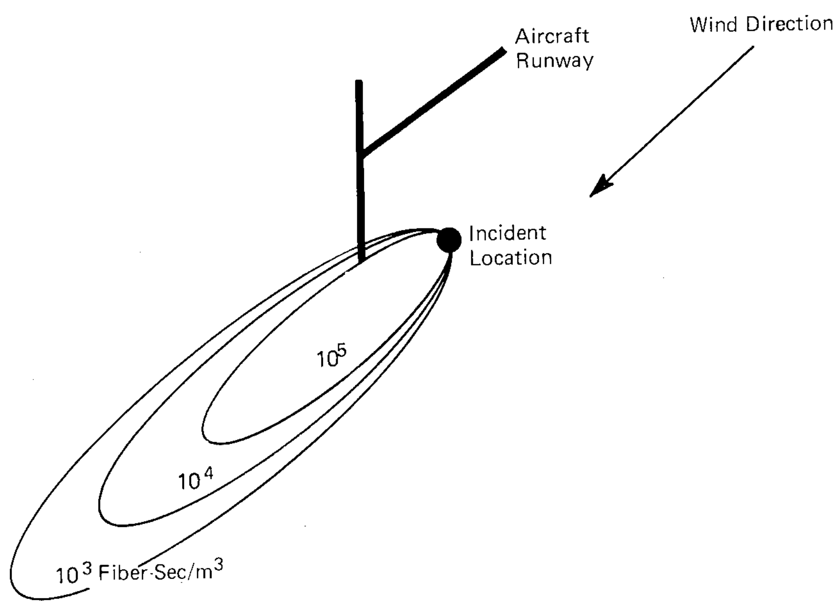


Figure 10.- Exposure footprints after carbon fiber release.

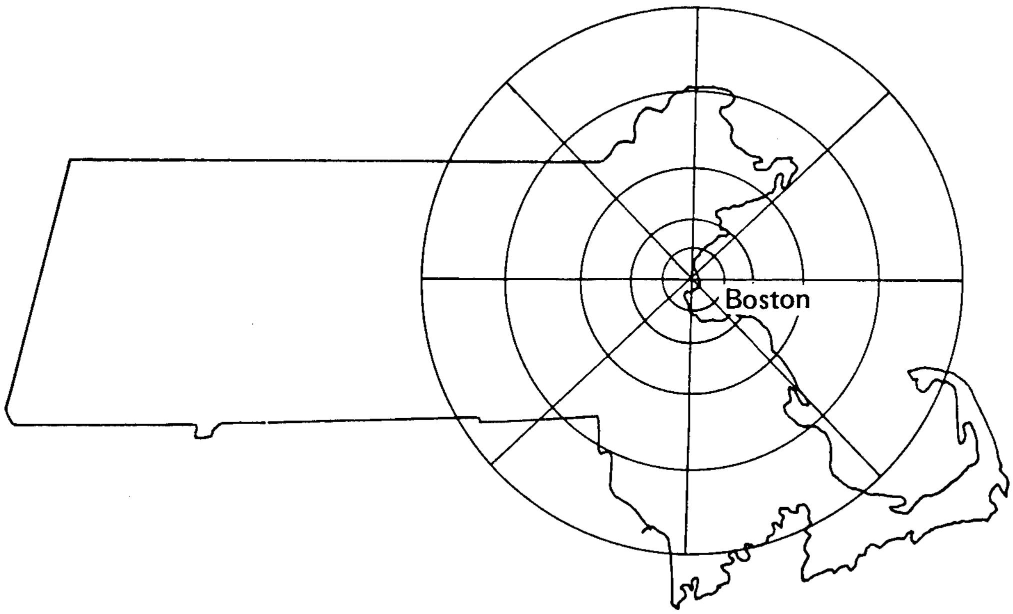


Figure 11.- Distribution of sectors around Logan Airport, Boston, Mass.

1. Residences	
2. Manufacturers	– Electronic Equipment
	– Computers
	– Aerospace
3. Transportation	– Aircraft and Air Traffic Control
	– Mass Transit
	– Railways
4. Communication	– Telephone
	– Radio/TV/Microwave
	– Post Offices
	– Fire/Police
5. Services	– Financial/Insurance
	– Software/EDP
	– Hospitals
6. General	– Retail Outlets
	– Office Buildings
	– Industrial Plants

Figure 12.- Potentially vulnerable facilities.

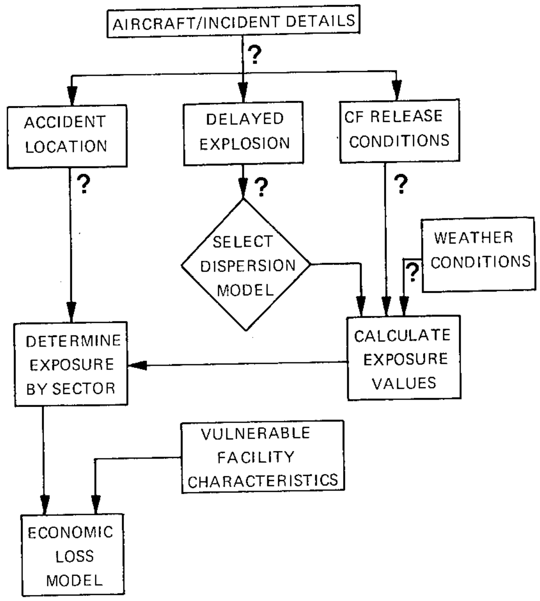


Figure 13.- Monte Carlo simulation procedure. (A "?" denotes a random draw.)

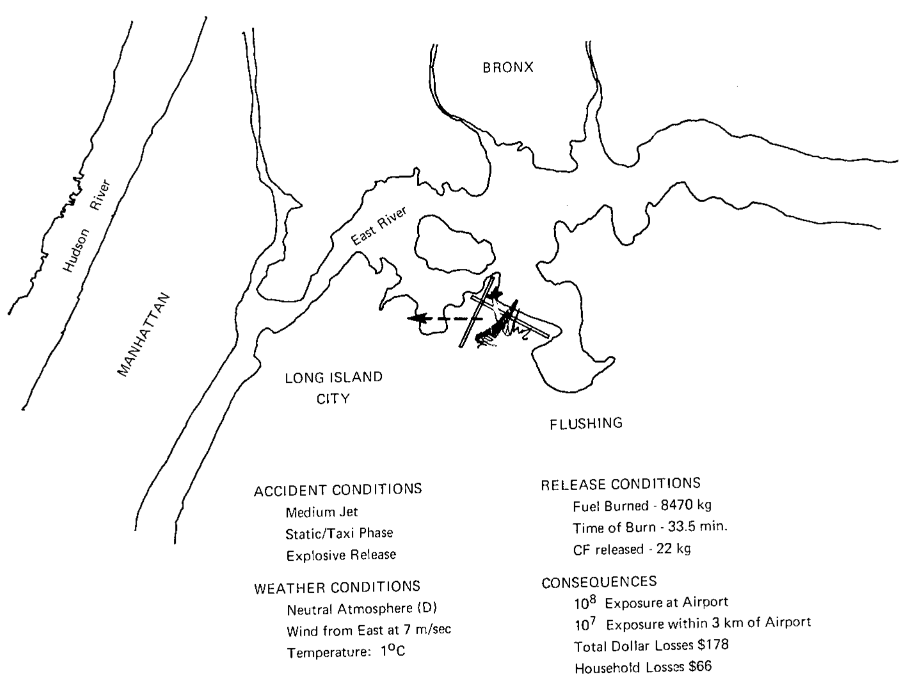


Figure 14.- Typical simulation run at LaGuardia Airport.

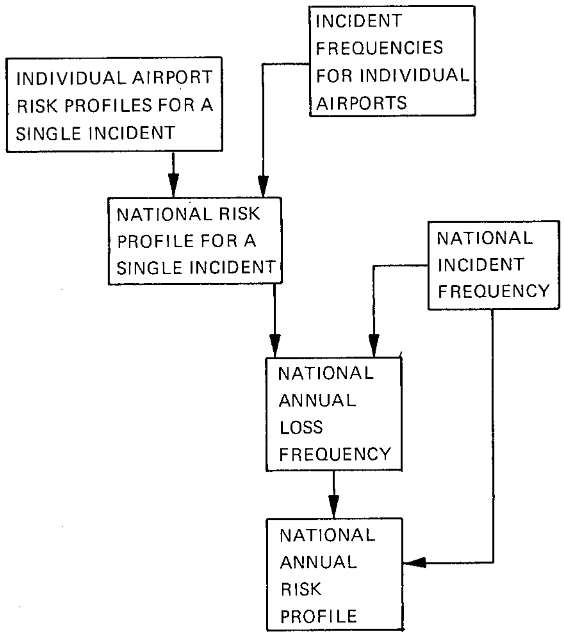


Figure 15.- Derivation of national risk profile.

1. Atmospheric conditions remain constant during dispersion of the carbon fiber cloud, and there is no precipitation
2. For a given facility category, all facilities are equal in size, equipment inventory, and financial characteristics
3. All equipments are in an activated state, and failures occur immediately after exposure

Figure 16.- Major assumptions.

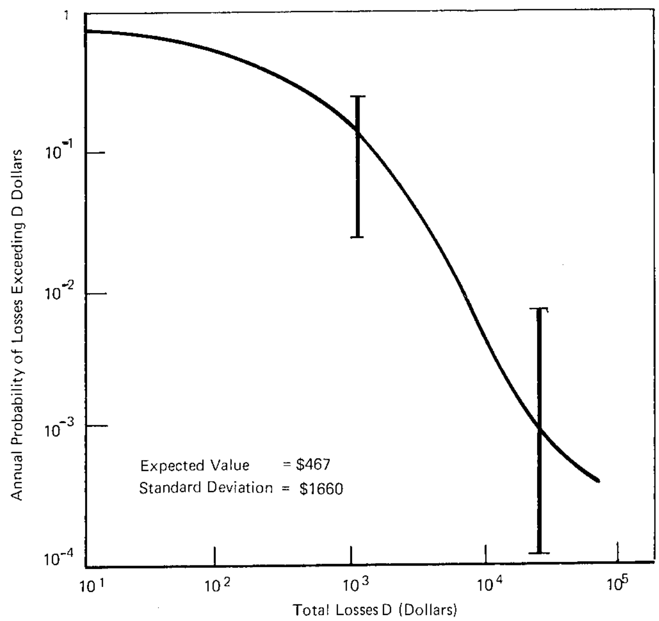


Figure 17.- National annual risk profile for carbon fiber releases from commercial air carriers (1993 CF utilization).

Changes in risk profile due to variation of input parameters, tested for the airport with highest mean dollar loss

Parameter Tested	Resulting Increases from Base Case: Mean Dollar Loss ($1184)	Standard Deviation ($2409)	Maximum Dollar Loss ($16,429)
Composite on Aircraft Set at Max. (15,652)	↑ by 7	↑ by 4.5	↑ by 4.5
100% Explosive Releases (no plume release)	↑ by 3	↑ by 2	↑ by 2.5
Stability Class Set at E (moderately stable)	↑ by 1.5	↑ by 1.2	↑ by 1.1

Figure 18.- Sensitivity analysis.

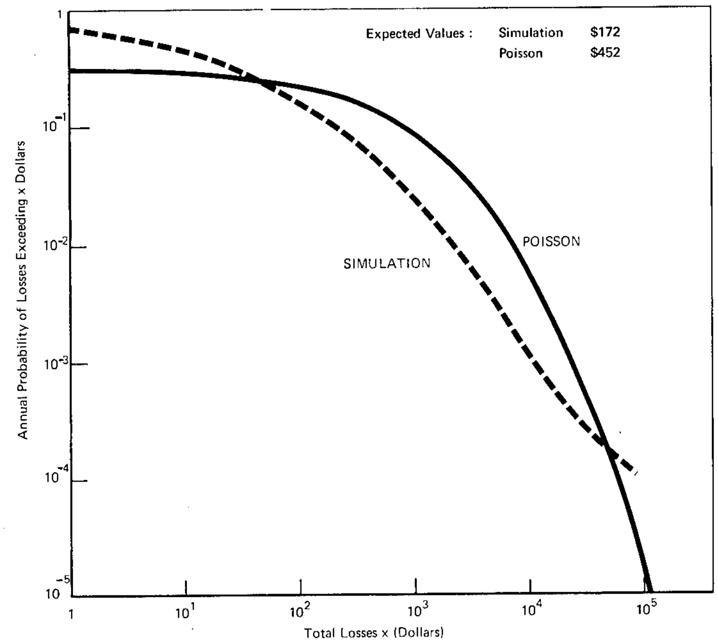


Figure 19.- Air carriers 1993 national conditional risk profile.

MAJOR OBJECTIVE

- Assess national risk of economic losses due to CF use in general aviation through 1993

SUB-OBJECTIVES

- Project potential usage of CF composites through 1993
- Investigate incidence of fires in general aviation aircraft within the U.S.
- Develop methods for assessing geographic distribution of potential economic losses
- Determine sensitivity of risk profile to uncertainties in input data

Figure 20.- General aviation risk assessment.

SIMULATION MODEL

- Appropriate for large releases near metropolitan areas
- Emphasizes variations in facility locations and release conditions
- Estimates of high loss probabilities subject to statistical uncertainty

ANALYTIC MODEL

- Appropriate when number of failures per release is small
- Emphasizes variation due to random nature of failure events
- Addresses variations in facility density between counties
- Requires only data on amount of CF released, similar to "single-fiber" concept

Figure 21.- Issues in choice of methodology.

- Estimate distribution of CF released in general aviation accidents
- Apportion accident locations by county based on air traffic activity
- Develop Poisson model for estimating the distribution of failures given an accident
- Use computer program to tabulate failure probabilities and aggregate economic losses
- Develop national risk profile based on estimated accident frequency

Figure 22.- Methodology overview.

D = Average Density of Equipment

S = Surface Integral of Exposure

E_o = Average Outside Exposure to Failure

E = CF Exposure at Any Location

For a given equipment type and release condition the expected number of failures is:

$$N_o = \int_{Area} \text{Density} \cdot (1 - e^{-E/E_o})$$

$$\approx \int_{Area} \text{Density} \left(\frac{E}{E_o}\right) \qquad \text{Since } E << E_o$$

For different release conditions but equivalent amount released

$$\text{Average } N_o \approx \frac{DS}{E_o}$$

When average N_o is small the variation in number of failures is predominantly due to the randomness of failure events

Figure 23.- Basis of Poisson approach.

	Growth Rate	No. of Aircraft in 1993	No. of Aircraft Carrying CF in 1993	Average CF Composite per Aircraft (KG)	CF Mass Released in Total Destruction Accident (KG)	CF Mass Released in Substantial Damage Accident (KG)
Single reciprocating engine	6.3%	321,000	80,250	7	.14	.034
Multi-engine and jets	4.8%	72,500	18,125	20.5	.41	.10
Helicopter, non-fixed wing, and non-powered	8.6%	25,000	6,250	54.5	1.09	.27

Figure 24.- Estimated usage of carbon fiber and potential releases (1993).

- Cruise accidents

  County probabilities are based on weighted average of local and itinerant operations

- On or near airport accidents

  County probabilities are based on number of operations

- 30% of operations accounted for. Other operations allocated to counties within each state according to population

Figure 25.- Distribution of general aviation accidents.

Frequency

340 fire accidents per year, of which 85 would involve CF.

Air taxi and commuter would raise this to 88

Relative likelihoods of accident types:

	Cruise		On or Near Airport	
	Total Destruction	Substantial Damage	Total Destruction	Substantial Damage
Non-fixed or non-powered	.072	.013	.043	.014
Single reciprocating	.333	.023	.203	.034
Multiple or jet	.101	.014	.122	.028

Figure 26.- General aviation accident data (1993 projections). (Source: NTSB accident statistics, 1968-1976)

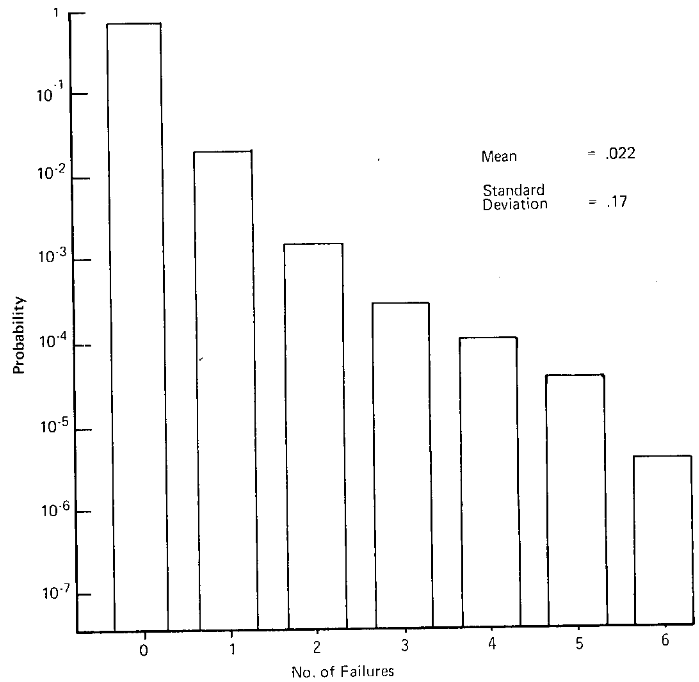


Figure 27.- General aviation 1993 probability distribution of number of equipment failures per accident.

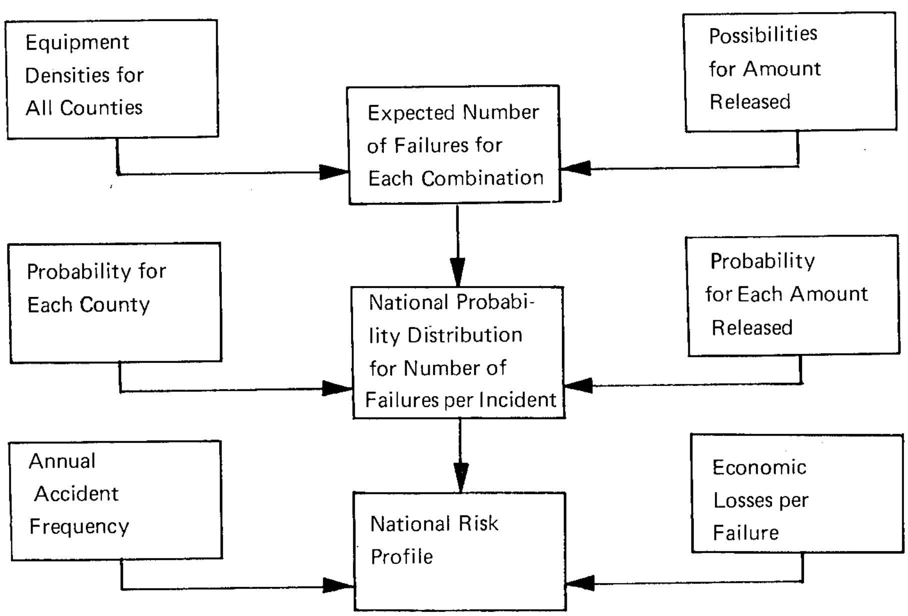


Figure 28.- Risk analysis procedure.

Dollar losses

Mean (per accident): $2.88

Standard deviation (per accident) $114

Mean (annual) $253

Standard deviation (Annual) $1067

Upper bounds for annual loss

$	Prob(Loss≥ $)
10,923	10^{-2}
106,953	10^{-4}
1,067,253	10^{-6}

Figure 29.- Result of risk analysis 1993.

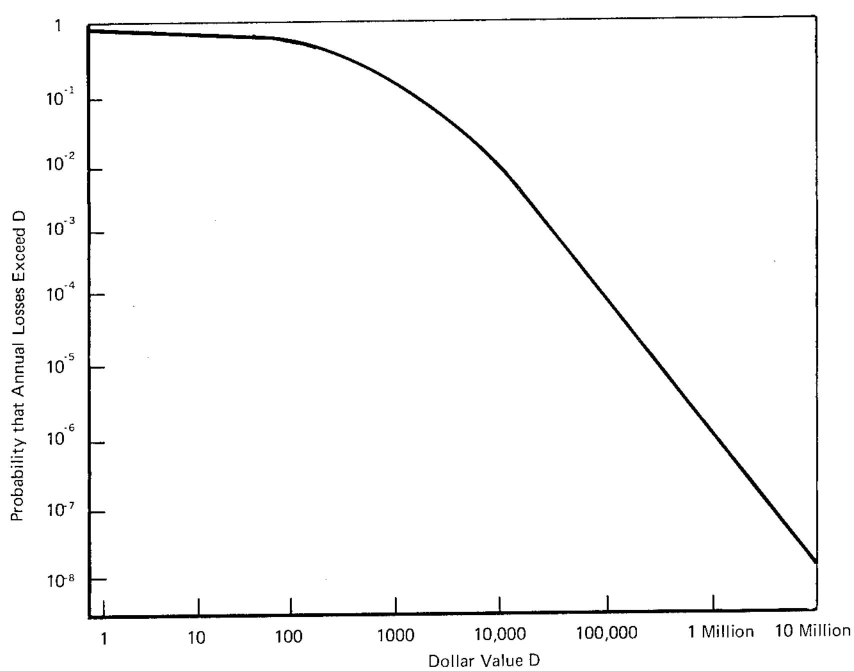


Figure 30.- Approximate upper bound on national risk profile for general aviation accidents (1993).

- Increase in amount released - direct effect on upper bound probabilities

- Increase in equipment vulnerability - direct effect on upper bound probabilities

	<u>E.G.</u>
	CF increases by 10
or	$\bar{E}$ decreases by 10
then	The probabilities go up by 10

$	Prob (annual loss ⩾ $)
106,953	10^{-3}
1,067,253	10^{-5}
10,670,253	10^{-7}

Figure 31.- Sensitivity analysis.

Perspective on the Results

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NASA Langley Research Center

This paper is an effort to put some of the things that we have found from the NASA study into perspective. I would like to start out by covering some issues that were not covered in detail in our discussions (Figure 1). One of the questions that we were originally asked was: is additional aircraft protection required? You should have noticed that air transport aircraft were included in the calculations of the risk profile, and, in fact, in the specific examples that were cited, you noted that the expected losses at the various airports were quite low. Independently, we have had Boeing, Lockheed, and Douglas analyzing each of their own aircraft, using fiber dissemination footprints that have been calculated for crash fires and explosions on an airport where quite high exposures have been predicted. We found, in the analysis of the aircraft systems, that the key issue that prevented aircraft from being considered perhaps totally invulnerable was the fact that occasionally aircraft avionic bay doors would be open. On those occasions, we found that the interior exposure was sufficient to fail one or two pieces of avionics equipment in a fleet of aircraft that were sitting on the ground where an aircraft accident had occurred. That fact suggests that some precautionary measures may be prudent. If you have an aircraft crash fire releasing carbon fibers on an airport it makes sense to close the doors on the aircraft and not allow interior exposure to carbon fibers.

We have also looked at fire-release strips as a possible cause of power interruptions. Our calculations show that only at a probability of one chance in a thousand will we be able to get power interruptions from the kind of composite strips that were generated at China Lake and Dugway Proving Ground tests. This kind of failure, incidently, is equivalent to the interruption that occurs when a squirrel shorts a powerline to ground.

The generation of composite strips and, in fact, the amount of carbon fiber debris that is actually found after a fire, suggests very clearly that carbon fiber debris should be cleaned up. Dr. Bell's paper, Reference 1, showed the mass balance distribution of carbon fiber from burned composites. The amount of debris or residue was quite large, in fact, many times the amount of free fiber that is released by the burn. Therefore, prudent practice would suggest that the aircraft owner go in and clean up the composite debris of an accident to prevent a secondary release of fibers. At this time it is the responsibility of an aircraft owner to clean up an accident so the extension of that requirement to include composite debris would be normal practice.

It should be pointed out that some unique carbon composites could be developed in the future. The term unique here applies to a carbon composite which has a release characteristic different from the average. Dr. Bell's paper described one composite with such a characteristic. It is possible that in the future, as additional carbon composite concepts are developed, other unique composites could turn up but we have also developed some test methods that are appropriate

for evaluating the fiber release characteristics. We think that these methods will be used to analyze the potential release from new concepts.

As for the assumptions inherent in this study, Figure 2 lists those that we feel result in a conservative final answer. Our analysis assumptions have included one percent release for a crash fire and 3 and a half percent release for a crash explosion. This assumption was based on the amount of material that we had found to be released from specimen tests. Based on the data recently acquired from the outdoor tests, we see considerably less release than that. Therefore we feel that our estimate is quite conservative here.

In the case of the explosive release model that A. D. Little uses (Reference 2), the analysis is considered to be conservative, that is it gives excessive fiber concentrations because it is really a ground-level fiber release and not an explosive plume that is carried up in the developed fire plume.

Our analysis at this point ignores the filter effect on fiber length. Dr. Elber's paper (Reference 3), showed that not only did filtration reduce the number of fibers that entered into either cases or buildings, but that it also provided an effective shortening of the fiber length spectrum. This phenomenon has a strong effect on the failure rate, as shown by Mr. Taback's paper (Reference 4). Therefore the fibers that enter a filtered enclosure are not as damaging as the fibers exterior to that enclosure. Our analysis has not included that effect.

We have based our equipment vulnerabilities on tests done with 1970 technology avionics and electronics. And as we see the future, electronics, avionics, and computer design and packaging is aiming towards low power, well-protected circuitry. Some of the more recent aircraft designs are utilizing totally air-conditioned avionics bays, primarily to increase the effective reliability of avionics. This effect is not considered in our analysis.

The equipment failure model over-predicts the failure rate for multi-fiber sensitive equipment. Test data described by Mr. Taback (Reference 4) shows the multi-fiber effect on equipment failure rates. There is a lot of equipment that we know requires multiple fiber contacts to initiate failure. In fact, anytime the electrical contact spacing exceeds the fiber length, shorting can occur only when two or more fibers bridge the space. From a practical sense, for this analysis, we don't think it is practical to try to even identify the multi-fiber sensitive equipment.

A final item on this list of conservative assumptions is that the analysis is made assuming that no precautions are taken against a known carbon fiber accident. Earlier, I pointed out that aircraft avionics can be effectively protected, when a crash fire occurs in an airport, by simply closing the avionics bay doors to prevent penetration by carbon fibers. Also, Mr. Taback (Reference 4) pointed out that in the worst case, the range of a scanning beam M.L.S. landing aid would be effectively reduced by 45% <u>if</u> an approaching aircraft was flown directly down the center of a fire released carbon fiber plume. Obviously, even present operating rules would not allow a second aircraft to approach an

airport directly over a burning aircraft where the crash cause was undetermined and could have been related to the operating condition of the landing aid. These examples of prudent precautions will obviously be expanded if cost effective measures are found suitable even with the current level of projected risk.

There are limitations in the analysis (Figure 3). One is that the data sample is small. We have only about 250 specimen burns in which to quantify the fiber release data. In addition, we have five outdoor tests in the most recent Dugway Proving Ground experiments that quantify the carbon fiber release. It is a small sample of data upon which to base our analysis. In addition, the total variety of equipment that we have examined for fiber vulnerability, either in the chamber here at Langley, at the Army Ballistic Research Laboratory, or in the work that has been done by the Department of Commerce Bureau of Standards, consists only of about 150 pieces of equipment. We have had to have quantified the vulnerability of all of the equipment considered nationally from a very limited number of tests. We are aware of and have considered other data in our analysis which is not available to the public.

One limitation that is important to recognize is that the structural concepts tested are considered typical of carbon composites of the future. Basically we have made the assumption that the structural concepts that we have available to us today are those which are going to be used in composite applications on aircraft built in the future.

We have not considered redissemination for the reasons that Dr. Elber (Reference 3) presented in his paper. In addition, a test in a clean wall and floor room showed that even a fan recirculating fibers increased exposure only about a factor of two. Both results indicate redissemination should not be a significant problem.

We believe that an accident clean up should include the accident debris, and as an assumed prudent measure, that would be a limitation of this analysis.

It should be pointed out that this analysis is limited to accidental release from civil aircraft and to damage done to residential, public, utility, commercial and industrial installations. What has been left out? The answer is very simple, what has been left out is the potential risk from military aircraft crashes and the potential damage to military sites. That is the subject of Department of Defense analyses.

It is appropriate to review the key findings of this study (Figure 4). We know that the release of fibers does require agitation of the composite residue. We see, from the evidence that we have, that a substantial portion of the carbon fiber is oxidized away. We see, from our specimen tests, that about one percent of the available fiber is released, but in our outdoor tests, we found only about 0.13 percent released or about a factor of eight conservative from our assumptions in our risk calculations. One final point is that most released single fibers are very short. This point should be amplified because we have had some specific examples of released fibers where the averages are longer than what we used in our analysis. A look at the sensitivity of

the risk estimates to the average fiber length is appropirate. If we normalize the risk at the 3 mm length used in the risk calculations, we can study the effect of fiber length on the risk. In our large scale tests in the Dahlgren shock tube, we found a mean fiber length of 2 millimeters. Now perhaps that is because of the extreme agitation of operating on the composite material with the rotisserie. However, in the outdoor tests we found a mean fiber length, in the worst case, of about 5 millimeters. Now, what is the effect of the mean fiber length on the mean exposure level for failure? Israel Taback (Reference 4) pointed out several possibilities. One possibility is that E bar is proportional to one over the length. Another possibility is that E bar is proportional to one over the length cubed. Figure 5 shows the effect of these two variations in the mean exposure to failure on the normalized risk assuming all equipment follows either one law or the other. The notation indicates the lengths obtained from the large scale tests. It is appropriate to point out that at least we have bracketed the large scale test data. The actual value of the risk could vary at the most, as a result of fiber length, by a factor of 2. Considering the fiber release characteristics as a whole, including percentage released as well as length, it would appear that we over-estimated the potential damage by somewhere between a factor of 4 and a factor of 8.

~~If we review the~~ key findings in the area of vulnerability of equipment, ~~(Figure 6), we find~~ that the damage done by released fibers is not as severe as once thought. The reason is that equipment vulnerability is lower for the currently acceptable structural fibers than for the very highly graphitic fibers once considered. If highly graphitic fibers (possessing modulus at elasticity two times that obtainable with current structural fibers) are found acceptable in the future, the base vulnerability level would have to be reevaluated. We ~~find from our~~ test data that vulnerability of domestic and industrial electronics and avionics is very low. The vulnerability of industrial electronics and avionics is low primarily because they are conformly coated and well protected. In addition ~~our~~ industrial power arc studies show that power vulnerability is low and unlikely to cause damage when properly fused. We have found that 110 volt motors and home appliances can not be hurt by carbon fibers.

Our present assessment of the risk, using current estimates of the carbon fiber release from civil aircraft and conservative vulnerability data, indicated that the expected annual cost is insignificant (Figure 7). A comparison of the results from the A. D. Little and the ORI studies (Figure 8) shows quite reasonable agreement. While the details of the risk profiles are slightly different, the expected annual cost for air transport for either is under $500. Adding the expected dollar loss from crash fires of carbon composite general aviation aircraft adds about 50% to the mean cost. Compared with the mean cost of the aircraft accidents the expected annual cost is an insignificant number. The FAA study of 1966-1975 aircraft accident costs (Reference 5) showed that the costs of air transport aircraft accidents range from less than a million dollars to nearly fifty million dollars (non-fire accidents are included). The mean cost of those accidents where the aircraft sustained at least substantial damage ranged from 5 million dollars for small jet aircraft to in excess of 10 million dollars for large jet aircraft. Therefore,

considering the annual number of aircraft crashes, the $500 annual potential damage from released carbon fiber must be compared with annual aircraft crash costs of nearly 100 million dollars (based on 1974 dollars). Considering that comparison, the worst case, low probability event is basically a low cost event. Figure 8 shows that there is only about one chance in 2000 of exceeding $150,000 damage annually. Our studies show that there is no need for additional protection of civil aircraft avionics, and the potential shock hazard is insignificant, hence risk to life should not be a consideration in carbon fiber applications.

In conclusion, we have some work to do (Figure 9). We have completed the planned work on the agreed to schedule. We will publish this conference proceedings, complete and publish the analysis of our large scale outdoor tests, and complete our final NASA summary report. NASA efforts in the carbon fiber hazard area will be completed when all NASA studies are published.

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ADDITIONAL AIRCRAFT PROTECTION IS NOT REQUIRED

PRECAUTIONARY MEASURES ARE PRUDENT

FIRE RELEASED STRIPS HAVE LOW PROBABILITY OF CAUSING DAMAGE

CARBON FIBER DEBRIS SHOULD BE CLEANED UP

UNIQUE CARBON COMPOSITES COULD BE DEVELOPED IN THE FUTURE

TEST METHODS ARE DEVELOPED FOR FIBER RELEASE EVALUATION

Figure 1.- Issues not covered in detail.

ANALYSIS ASSUMPTIONS 1% FIRE, 3 1/2% EXPLOSIVE RELEASE

EXPLOSIVE RELEASE MODEL GIVES EXCESSIVE FIBER EXPOSURES

ANALYSIS IGNORES FILTER EFFECT ON FIBER LENGTH

EQUIPMENT VULNERABILITIES BASED ON 1970'S TECHNOLOGY

MODEL OVERPREDICTS FAILURE RATES FOR MULTI-FIBER SENSITIVE EQUIPMENT

NO PRECAUTIONS TAKEN AGAINST KNOWN CF ACCIDENT

Figure 2.- Conservative assumptions.

THE DATA SAMPLE IS SMALL

STRUCTURAL CONCEPTS TESTED ARE TYPICAL OF THE FUTURE

REDISSEMINATION IS NOT CONSIDERED

ACCIDENT CLEAN UP INCLUDES COMPOSITE DEBRIS

ANALYSIS LIMITED TO:

- ACCIDENTAL RELEASE FROM CIVIL AIRCRAFT
- DAMAGE TO RESIDENTAL AND PUBLIC, UTILITY, COMMERCIAL AND INDUSTRIAL INSTALLATIONS

Figure 3.- Limitations in analysis.

- REQUIRES AGITATION OF RESIDUE
- SUBSTANTIAL PROPORTIONS ARE OXIDIZED AWAY
- 1% OR LESS RELEASED AS SINGLE FIBERS IN SPECIMEN TESTS
- 0.13% OR LESS RELEASED IN LARGE-SCALE OUTDOOR BURNS
- MOST RELEASED SINGLE FIBERS ARE VERY SHORT

Figure 4.- Key findings in carbon fiber risk analysis. Release of fibers by fire.

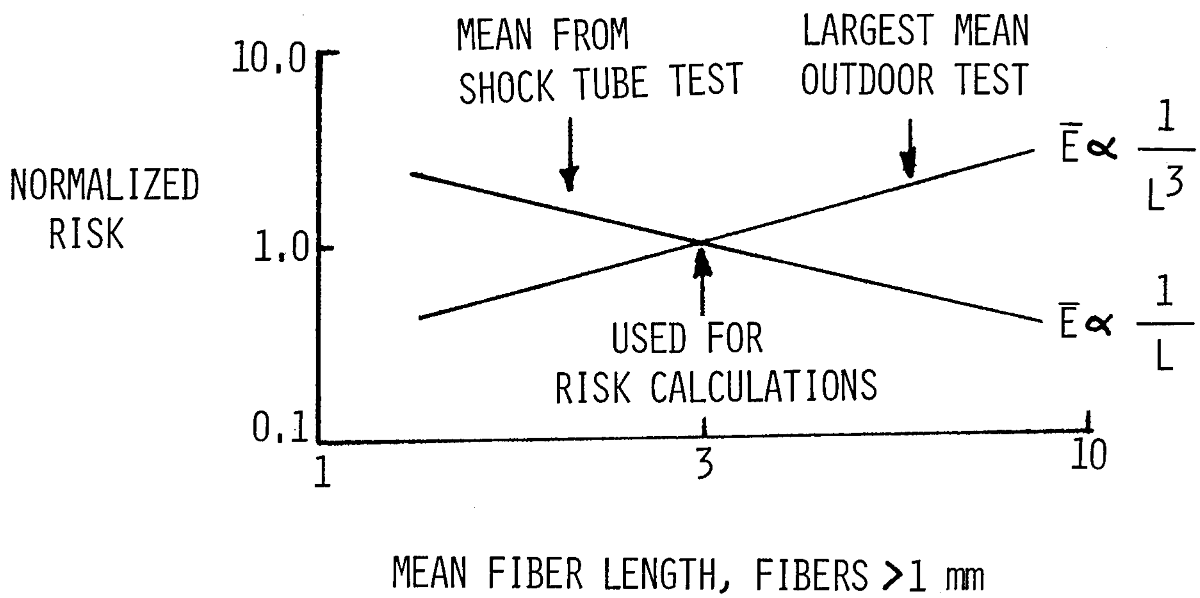

Figure 5.- Sensitivity of risk calculation to average released fiber length.

- LOW FOR CURRENT STRUCTURAL FIBERS
- HIGHER FOR HIGHLY GRAPHITIC FIBERS
- VERY LOW FOR DOMESTIC, INDUSTRIAL ELECTRONIC AND AVIONICS
- LOW FOR POWER SYSTEMS
- ZERO FOR 110-VOLT MOTORS AND HOME APPLIANCES

Figure 6.- Key findings in carbon fiber risk analysis.
Vulnerability of equipment.

- THE USE OF CONSERVATIVE ESTIMATES OF ACCIDENTAL CF RELEASE FROM CIVIL AIRCRAFT AND CONSERVATIVE VULNERABILITY DATA INDICATES THAT:
  - THE "EXPECTED ANNUAL COST" IS INSIGNIFICANT
  - THE WORST CASE, LOW PROBABILITY EVENT IS A LOW COST EVENT
  - NO ADDITIONAL PROTECTION OF CIVIL AIRCRAFT AVIONICS IS REQUIRED
  - THE POTENTIAL SHOCK HAZARD IS INSIGNIFICANT - HENCE RISK OF LIFE IS NOT A FACTOR

Figure 7.- Key findings in carbon fiber risk analysis. Present assessment of risk.

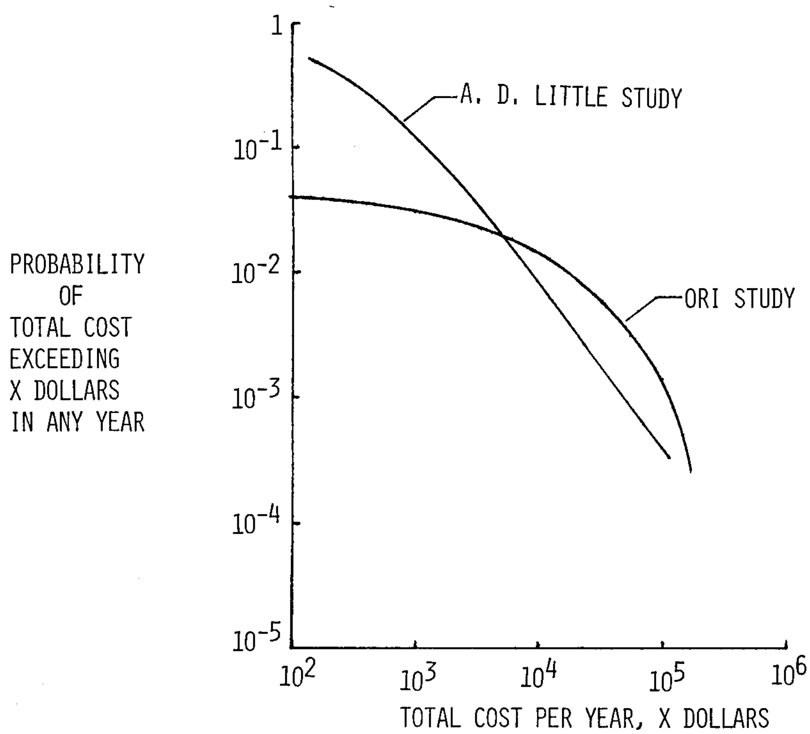

Figure 8.- National annual risk profile. Carbon fiber released from commercial air carrier accidents. (1993 CF usage.)

- REMAINING WORK

  PUBLISH CONFERENCE PROCEEDINGS

  FINAL ANALYSIS OF LARGE-SCALE OUTDOOR TESTS

  FINAL NASA REPORT ON PUBLIC RISK DUE TO ACCIDENTALLY RELEASED CF FROM CIVIL AIRCRAFT

- NASA EFFORT WILL BE COMPLETE UPON PUBLICATION OF ALL TEST AND STUDY RESULTS

Figure 9.- Conclusion of carbon fiber risk assessment.

CARBON FIBER DOMESTIC DATA BASE - MARKET ANALYSIS, PRODUCTION CAPACITY, AND COST PROJECTIONS

D. Parsons
U.S. Department of Commerce

[Unavailable at time of publication.]

A RESEARCH PROGRAM IN WASTE MANAGEMENT

TECHNOLOGY FOR CARBON FIBERS

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In FY 1978 the U.S. Environmental Protection Agency (EPA) began developing a research and development program to address potential problems which may arise from the release of carbon fibers into the environment. The program consists of two parts: Carbon Fiber Characterization and Measurement Technology Development and Carbon Fiber Waste Management Technology Development (Figure 1). The Environmental Sciences Research Laboratory is developing the program for Carbon Fiber Characterization and Measurement Technology. We at the Municipal Environmental Research Laboratory are responsible for the Carbon Fiber Waste Management Technology program. Both of these laboratories are part of EPA's Office of Research and Development and Richard A. Carnes is the Agency's Coordinator for Carbon Fiber Research.

EPA's budget for the first five years of the carbon fiber program is shown in Figure 2. By the end of this fiscal year, it is planned that all funds will be allocated for the characterization and measurement program. The annual funding for the waste management technology development program is expected to range from $600,000 to $1,000,000 between FY 1979 and FY 1982.

Carbon Fiber Waste Management Technology Development program being carried out by EPA's Municipal Environmental Research Laboratory was initiated in late FY 1979 with technical contracts awarded in three task areas. During FY 1980 and 1981 additional technical contracts will be awarded in four task areas. Long range plans call for further contract awards in five task areas in the FY 1982 period and beyond. The program has three objectives: (1) characterization and assessment of the carbon fiber problem, including market penetration studies, (2) development and demonstration of carbon fiber control technology (in the broadest sense, including process changes, etc.) and (3) assessment of the legal, economic and social impacts of carbon fiber regulation and control.

The three tasks which were initiated during late FY 1979 are described below. A complete assessment will be performed by Bionetics of existing information on the environmental implications of the carbon fiber problem including hazards, ambient concentrations and geographical distributions, existing control mechanisms, disposal techniques and risk assessment. The task includes several subtasks. Materials for these subtasks require a close liaison with all programs in other agencies and an incorporation of all pertinent information into the EPA program. The initial subtask is to perform a literature search to identify problems encountered by the release of carbon fiber during handling and disposal, uses of carbon fibers, potential health

effects, and information related to the properties, production, manufacture, and resins applications. Based on this literature search, several sets of summary data tables will be prepared. Tables will summarize the type and number of present and/or proposed research military aircraft and transport aircraft which utilize a carbon fiber. Summary tables will be developed for information on carbon fiber manufacturers and their products. The objective of the second subtask is to define risk considerations as interpreted by various Federal agencies, compile their risk assessment programs, and identify areas of concern and data requirements. The third subtask required the preparation of a directory and locator for principal individuals participating in carbon fiber programs. Efforts on the fourth subtask are ongoing. The purpose of this subtask is to predict the average concentrations required to cause failure in the types of electrical equipment used for solid waste management; to calculate transfer functions for solid waste management facilities and enclosures for equipment; and to estimate free fiber characteristics at solid waste locations. Review of present disposal methods is an important part of subtask 5 and accordingly a visit has been made to the refuse incinerator at Saugus, Massachusetts. Finally, a subtask has been undertaken to develop scenarios for carbon fiber life cycles from raw product to ultimate disposal covering the range of potential usage in commerce. Additionally, critical points and potential areas relative to hazards for both individuals and the environment will be defined. We anticipate the completion of all these subtasks early in 1980.

A separate effort has been undertaken by Econ of Princeton, New Jersey. The objective of this effort is the quantification of the current and projected uses of carbon fiber composites in the production of consumer products, evaluation of the potential threats to society from accidental discharge of carbon fibers to the environment and assessment of the economic tradeoffs associated with the use and/or restriction in the use of this material. As this is a 2-year effort the first major results are not expected until late 1980/early 1981.

Researchers at the University of California at Berkeley are working on the assessment of the effects of carbon fiber composite materials in solid waste processing. This task will involve the use of a laboratory scale 9072 kg/hr (10 ton/hr) shredder, a 2722 kg/hr (3 ton/hr) continuing system, and associated equipment to investigate the effects of processing solid municipal waste containing projected typical amounts of carbon fiber wastes. The assessment will cover (1) comparison of the processed waste with conventional municipal solid waste, (2) effects of the carbon fiber waste on the processing machinery, including wear and tear and power consumption, (3) evaluation of fugitive dust at various locations in the process, worker exposure and possible pathways to the ambient environment, and (4) preparation of a number of refuse derived fuel (RDF) and densified RDF samples in order to test wear on equipment and power consumption in comparison to conventional solid waste.

Four tasks are programmed to be initiated during FY 1980 or 1981. The task with the highest priority is research on incineration. Combustion tests will be conducted on three types of pilot-scale incinerators to compare emission characteristics of conventional municipal solid waste with municipal solid

waste seeded with carbon fiber material. Emission control will be the best available technology for the control of particulate matter for both types of waste. It is the purpose of this study to determine if carbon fiber materials disposed of in the municipal solid waste sector by incineration will pose a potential environmental hazard should incinerator emission contain significant amounts of free fibers. Investigation will cover changes in the combustion process itself, characterization of emitted carbon fibers and changes in conventional emissions. Residue from the process will also be carefully analyzed for carbon fiber content.

Three other tasks are planned. The first is an evaluation of carbon fiber waste impacts on existing and emerging disposal and resource recovery systems. This will include a study of trends in the use and application of current and emerging solid waste management technologies, identification of those processes or steps which will receive substantial carbon fiber impact and identification of those most likely to cause significant atmospheric emissions of carbon fiber.

The second is an evaluation of measures to mitigate the impact of carbon fiber on municipal solid waste technologies such as source separation, modification of resins, production changes, modified or partial bans and labeling.

Another task will evaluate carbon fiber discharge test results and determine the adequacy of current and future solid waste processing, recovery and disposal technology to eliminate carbon fiber hazards. This includes identification of technologies which must be modified or newly developed to adequately control discharges and an estimate of the research and demonstration efforts required.

Tasks to be initiated during FY 1982 or beyond may include:

- Evaluation of the legal, economic, environmental, social and political impacts of instituting necessary modifications to current and projected solid waste management systems. These impacts will be evaluated in light of the various risk assessments conducted previously by EPA and other agencies.

- Evaluation of carbon fiber disposal demonstration research in three areas: (1) full-scale incineration studies, (2) RDF and densified RDF combustion, and (3) evaluation of a small particle collection device for controlling carbon fiber emissions.

EPA is pleased to have the opportunity to participate in this meeting as it will help to insure the development of carbon fiber research programs which are compatible with the on-going and planned programs of other organizations. We look forward to working with all of you in the future on this interesting and important environmental program.

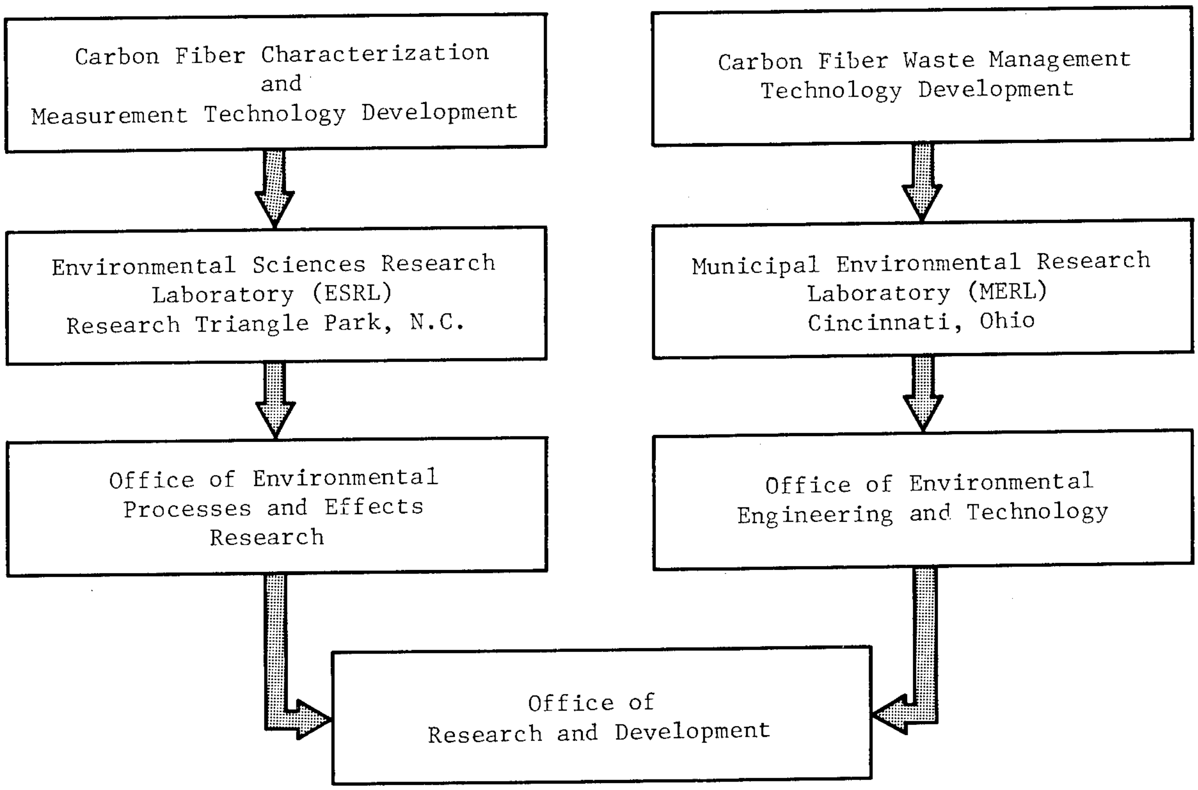

Figure 1.- EPA's carbon fiber program.

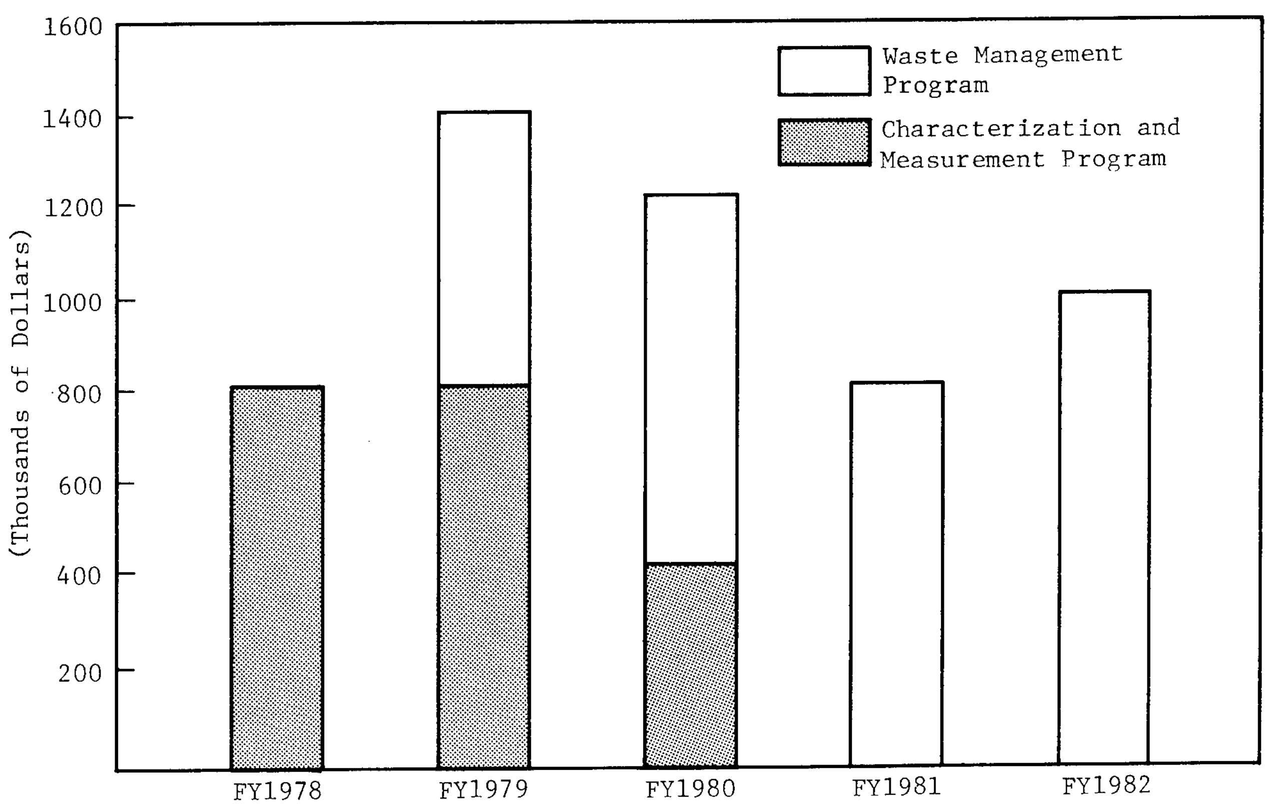

Figure 2.- Five year carbon fiber budget plan.

CARBON FIBER MONITORING RESEARCH PROGRAM

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Environmental protection depends on efforts to detect, identify and quantify specific pollutants and to assess their effects. In anticipation of projected increases in the production and usage of carbon composite materials, the Federal Government action plan on the Carbon Fiber Hazard assigned to the Environmental Protection Agency the responsibility for developing capabilities for source and ambient air monitoring of released carbon fibers from manufacturing and waste disposal facilities. The research program to achieve these capabilities is being conducted by the EPA Environmental Sciences Research Laboratory (ESRL) at Research Triangle Park, North Carolina.

The present ESRL program consists of a number of projects that were initiated in fiscal year 1979 and are being carried out primarily through contracts, grants and interagency agreements. Studies under way fall into three categories as follows:

1. Carbon fiber emissions characterization

2. Measurement techniques for carbon fiber emissions

3. Measurement techniques for atmospheric concentrations of carbon fibers

CARBON FIBER EMISSIONS CHARACTERIZATION

A two-year study has been initiated (August 1979) through a contract with Battelle-Columbus Laboratories for the "Characterization of Carbon Fiber Emissions from Current and Projected Activities for the Manufacture and Disposal of Carbon Fiber Products." Tasks to be performed include:

- Determination of mass concentrations, number concentrations, and size distributions of fibers emitted during manufacturing and incineration of carbon fiber products

- Determination of chemical, morphological and other physical properties

- Estimation of the material damage potential of emitted fibers, including damage to standard electrical and electronic devices

Since extramural research programs require considerable lead times before they can be implemented, some preliminary in-house experiments (ref. 1) were

carried out early in FY 1979, using available facilities and instrumentation, with the objective of obtaining a rough characterization of dusts and other debris resulting from the machining and incineration of graphite/epoxy composites. While these experiments involved only laboratory simulations of actual or projected operations, it was felt that they could yield some useful information on the nature of potential carbon fiber emissions.

Examination of residues after exposure of graphite fibers and fiber/epoxy composites to elevated temperatures in a laboratory tube furnace demonstrated the high resistance of graphite fibers to combustion at temperatures up to 1000°C. Resins and binders in composites were destroyed rapidly but the fibers remained intact for significant periods even at 1000°C. (See figure 1.) Resistance of fibers to damage varied from product to product and probably depends on degree of graphitization. Damage was first observed in the form of dimpling and thinning of the fibers after exposure for some minutes at 1000°C as shown in figure 2. One can predict from these results that the disposal of graphite/epoxy composite waste materials by conventional refuse incineration would result in the release of large amounts of both intact and partly degraded graphite fibers.

Dusts generated by sawing or drilling of graphite/epoxy composites contained significant numbers of fibers free of the resin matrix. These fibers generally had lengths of about 50-100 μm. There was also evidence that sawing can cause longitudinal cleavage of the fibers, thereby making possible the generation of more respirable fiber fragments with diameters less than that (about 6-8 μm) determined in the fiber manufacturing process.

MEASUREMENT TECHNIQUES FOR CARBON FIBER EMISSIONS

The needs for two types of measurement methods for carbon fiber emissions are being addressed in the current program. One of the needs is a method that is highly specific for carbon fibers and can serve as a reference analytical procedure. Such a procedure is the objective of an 18 month study for the "Development of a Method for the Positive Identification and Measurement of Carbon Fiber Concentrations Emitted from Stationary Sources." This project began in August 1979 through a contract with Battelle-Columbus Laboratories.

The other need being addressed is an instrumental method that can be used for continuous monitoring of carbon fiber emissions. This is perhaps the most important objective in the program, inasmuch as a capability of this kind would permit real-time verification of the effectiveness of emission control measures at manufacturing facilities, incinerators, and other possible sources. To achieve this objective, an 18-month project for the "Evaluation and Development of Instrumentation for Monitoring Carbon Fiber Emissions" was started in October 1979 with the participation of the Bionetics Corporation, GCA Corporation, Arthur D. Little Inc. and TRW Inc. This two-phase effort will consist of the following tasks:

Phase I: Evaluation

- Survey of existing carbon fiber sensors
- Identification of monitoring requirements
- Laboratory performance tests of candidate sensors
- Rank sensors; identify development needs

Phase II: Development

- Design and construct prototype monitoring system
- Develop field calibration procedure
- Laboratory evaluation of prototype
- Field evaluation at selected sites

ATMOSPHERIC MEASUREMENT METHODS DEVELOPMENT

The EPA carbon fiber monitoring research program is also addressing the need for measurement technology to determine ambient air concentrations of carbon fibers. This capability is needed for problem assessment applications, including the monitoring of areas near known major sources and the determination of long-term trends in airborne fiber levels.

Current projects were initiated late in FY 1979 as follows:

- <u>Optical and Chemical Measurement of Carbon Fibers</u>. A two-year study through a contract with Bionetics Corporation involves the development of analytical procedures for carbon fibers collected on membrane filters. Methods to be studied include carbon fiber mass determination by high temperature combustion and fiber counting by light scattering.

- <u>Development of Generator and Low-Cost Sampler</u>. A research grant has been awarded to the University of Minnesota for the development of a procedure to generate well-defined carbon fiber aerosols and an economical carbon fiber collector for ambient air use.

- <u>Development of Continuous or Semi-Continuous Measurement Methods for Carbon Fibers</u>. A two-year project at the Lawrence Berkeley Laboratory, funded through an interagency agreement with the Department of Energy, involves the evaluation of alternative sampling and analysis strategies, and the design, fabrication and testing of a prototype sampling and analysis system.

Characteristics and Environmental Effects of Carbon Fiber Aerosols. Through a research grant to the University of Arkansas, a three-year project is in progress to study carbon fiber release mechanisms, aerodynamic transport properties, and surface deposition characteristics. The development of a continuous ambient air monitor is another objective.

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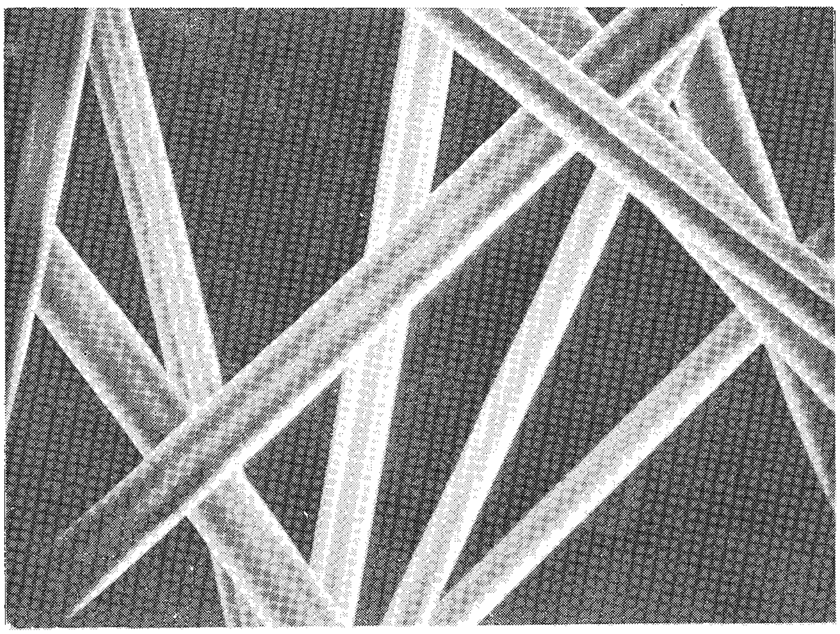
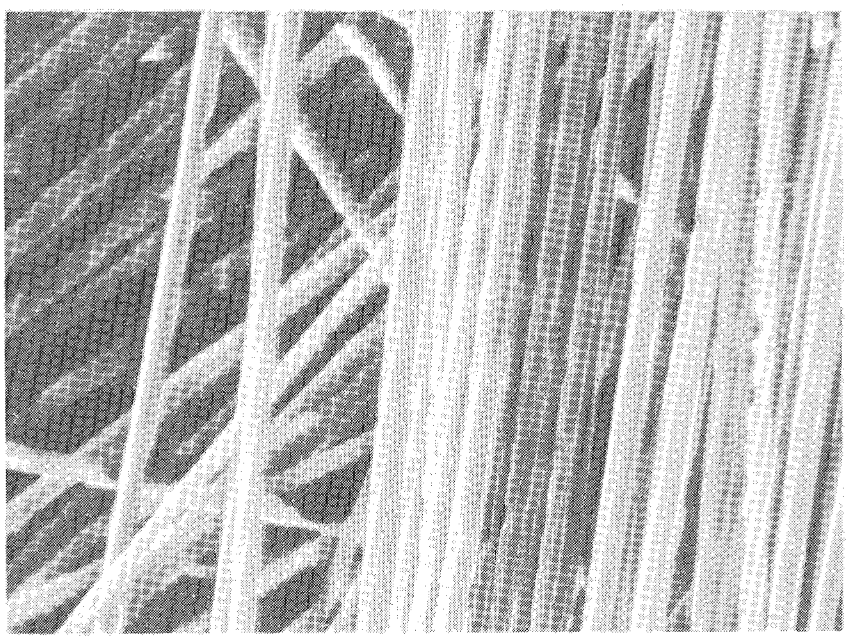


10 μm

Figure 1.- SEM micrograph of fiber residue following exposure of graphite/epoxy sample [Fortafil 5 (Great Lakes Carbon)] for 5 minutes at 1000° C.



10 μm

Figure 2.- SEM micrograph of carbon fibers [Thornell 300 (Union Carbide)] after exposure for 3.5 minutes at 1000° C.

EFFECTS OF CARBON/GRAPHITE FIBER CONTAMINATION ON HIGH VOLTAGE ELECTRICAL INSULATION

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THE NATURE OF THE PROBLEM

The burning and/or explosion of carbon/graphite composites has been demonstrated to release large numbers of small, electrically conductive carbon/graphite fibers into the atmosphere. These fibers are propagated by air currents over large areas as they settle back down to the earth. The length spectrum, electrical conductivity and propagation characteristics have been characterized in detail by others. During the course of air propagation and settling, these conductive fibers come in contact with all structures located in the propagation path, including electrical power systems. The electrically conductive nature of these fibers caused concern over the potential effects of exposure to electrical power systems. To determine the degree of hazard posed, the U.S. Department of Energy, through its contractor, Westinghouse Electric Corporation, initiated a testing and evaluation program to quantify the effects of carbon/graphite exposure to high voltage electrical insulation and to power plant and substation control systems. This work was carried out in close cooperation with the NASA risk assessment program.

POWER SYSTEM COMPONENTS

The basic elements of a power system are shown, in simplified form, in Figure 1. These basic elements consist of:

1) Power plants
2) Bulk power substations
3) Transmission system
4) Transmission substations
5) Subtransmission system
6) Distribution substation
7) Distribution system
8) Utilization voltages

All of these components may be exposed to carbon/graphite fiber contamination. The areas of investigation are the vulnerability of high voltage insulation and the vulnerability of power plants

and substation control systems. These areas encompass all of the eight enumerated power system components except utilization voltages. The vulnerability of utilization voltage installations and industrial plants is being evaluated by others.

The evaluation of high voltage insulation vulnerability to carbon/graphite fiber-induced failure required implementation of a laboratory testing program. A contamination test chamber was constructed, a fiber chopper was built and a high voltage power supply was assembled. Representative samples of distribution class (2400 Volts to 35 kV) and transmission class (over 35 kV) insulators were selected for testing.

CONTAMINATION SYSTEM

The contamination system includes the fiber chopper, dispersal chamber, air ducts and blower, and contamination chamber. A floor plan of this system is shown in Figure 2.

Fiber Chopper

The fiber chopper is a multi-knife roller type manufactured by Binks which was modified to cut the relatively light-weight carbon fiber and to operate at low speeds. Figure 3 shows a schematic of the chopper. This chopper has various multi-knife rollers to cut different lengths of fiber. During normal operation, a single end of fiber is fed off a 114-g (1/4-lb) roll into the chopper.

Dispersal Chamber

The dispersal chamber was designed to mix air with the chopped fibers and collect any clumps of fibers which may be generated by the chopper. A diagram of the dispersal chamber is shown in Figure 4. The dispersal chamber is constructed entirely of clear LEXAN sheeting material so its operation is clearly visible from the outside.

Contamination Chamber

The chamber provides dispersion and confinement of the fibers and maximum visibility of the test object. The layout of the chamber is shown in Figure 2. The chamber is constructed of .64-cm (.25-in) LEXAN sheeting coated with an anti-static compound and assembled with structural fiberglass and nylon fasteners. Structural members are external so the inside walls are smooth and clear of any projections to prevent any accumulation of fibers and to facilitate cleaning of the chamber. The dimensions of the chamber are 2.44 x 2.44 x 3.05 meters (8′ x 8′ x 10′).

Air Ducts and Suction Blower

The air ducts and suction blower transport the chopped fibers from the dispersal chamber into the contamination chamber. The suction blower also collects fibers during the contamination tests and during the clean-up of the chamber after a test. The air flow through the contamination

chamber is controlled by an air by-pass at the suction blower. The location of the air ducts and suction blower are shown in Figure 2.

Lighting

Experiments were made with light positioning to obtain the best view of the test. The transparent chamber made changing light positioning simple. Finally, three 150 watt spotlights mounted in a triangle arrangement over the test object were found to allow good visual observation of the airborne fiber movements.

HIGH VOLTAGE POWER SUPPLY

IEEE Standard 4, "Standard Techniques for High Voltage Testing" recommends that a high voltage supply with an rms fault current of at least three to six amperes should be used for artificial contamination tests. Testing experience has shown that these fault current capabilities will result in five percent or less error in determining the disruptive discharge voltage. Therefore, the main design criterion selected for the high voltage supply was that it should produce at least 5 amperes of fault current at the lowest contemplated test voltage, 4 kV. There is no guarantee that the IEEE recommendations will apply directly to carbon fiber testing, but it is the best guideline available for contamination testing.

In order to minimize cost and delivery time, it was decided to design the high voltage supply using standard distribution transformers rather than ordering a custom built supply. In this particular design a distribution transformer can be energized from a 240 volt supply and the voltage stepped up to distribution class levels. A standard variable autotransformer can be used to adjust the test voltage by varying the voltage supplied to the low voltage side of the distribution transformer. It soon became apparent in pursuing this design that severe requirements are placed on the autotransformer if a single distribution transformer is chosen to supply test voltages from 4 kV up to approximately 30 kV. If a single distribution transformer was selected to supply 5 amps of fault current at 4 kV, then the fault current at 30 kV would be 37.5 amps. 37.5 amps of current supplied at 30 kV would subject the variable autotransformer to approximately 4,700 amps of current during an insulator flashover. The 4,700 amps of fault current is beyond the capability of readily available variable autotransformers. Considering the variable autotransformer limitations and distribution transformers which were readily available, it was decided to design the high voltage supply utilizing two different configurations. Figure 5 shows the configuration used for supplying test voltages from 4 kV to 15 kV and Figure 6 shows the supply configuration for producing test voltages from 15 kV to 30 kV.

By using the single distribution transformer scheme shown in Figure 5, fault currents of 5.6 amps and 21 amps were supplied at test voltages of 4 kV and 15 kV respectively.

In the scheme shown in Figure 6, three distribution transformers were placed in cascade to produce test voltages from 15 kV up to 30 kV. The fault currents available range from 4.5 amps at 15 kV to 9 amps at 30 kV. With this configuration the distribution transformer at ground potential steps the voltage up to 15 kV and energizes the transformers on the insulated platform. The transformers on the insulated platform then boost the test voltage by another 15 kV for a total of up to 30 kV on the test object. In later tests on transmission voltage class insulators two more dis-

tribution transformers were placed in cascade with the first three transformers to produce test voltages up to 45 kV line-to-ground.

Fiber Selected for Testing

Celanese GY-70 fiber was selected. It was used in all of the contamination tests. At high voltages the fiber resistivity becomes relatively insignificant. GY-70 was selected because of ease of chopping and its resistance to clumping after being chopped.

Fall Velocity Measurement

An improved method was developed for measurement of the mean fiber fall velocity during chamber operation. To measure fall velocity two sticky tapes were placed in the chamber, one covered and the other uncovered. The chopper was operated for 15 minutes. The chopper and blower were turned off and the second sticky tape uncovered allowing fiber in the air to settle on the sticky tape. If fibers from top to bottom of the chamber is assumed to be evenly distributed the number of fibers on the sticky tape uncovered at chopper shutdown corresponds to the fiber in a volume of air above it at the time of shutdown so concentration can be determined. The total 15 minute sticky tape count corresponds to the total amount of fiber chopped. Determination of velocity was made as follows:

E	=	Exposure
S_1	=	Fiber count on sticky tape uncovered at chopper shutdown
S_2	=	Fiber count on sticky tape left uncovered through the entire test
$\overline{C}$	=	Average concentration
V	=	Fiber velocity
vol	=	Volume above sticky tape
T	=	Total time chopper was run
C	=	Concentration

Then:

$$E = \frac{S_2}{V} = \overline{C} \times T \tag{1}$$

Solving for V:

$$V = \frac{S_2}{\overline{C} \times T} \tag{2}$$

but if it is assumed that average concentration is approximately the concentration at shutdown:

$$\overline{C} \cong C = \frac{S_1}{\text{vol}} \tag{3}$$

So,

$$V \cong \frac{S_2 \times \text{vol}}{S_1 \times T} \tag{4}$$

This method provides an alternate way of determining fiber fall velocity. Several tests were performed and the average velocity for 2 mm tests was determined to be 2 cm/sec.

CONTAMINATION TESTING

Several representative samples of distribution class insulation were selected for testing. These are enumerated in Table 1. The samples include pin insulators, line posts, station posts, transformer bushings, and suspension insulators. Rated voltages range from 5 kV to 34.5 kV. The samples selected cover the range of generic classes of distribution insulation present on modern power distribution systems throughout the United States.

Test Procedure

Each test was begun by mounting an insulator in the chamber and placing sticky tape near it. After the chamber door was sealed rated voltage was applied to the insulator and the charged ball detectors were activated. Then fiber material was injected into the chamber until flashover.

After flashover the fiber chopper was shut off, the fiber count from the charged balls and the time to flashover recorded, and the sticky tape removed and a count made.

Three parameters were monitored during tests; exposure, fiber length distribution, and concentration. These characteristics were monitored with sticky tapes and charged balls.

The sticky tape count is used to determine exposures up to 10^7 fiber-sec/m^3, but for greater exposures accurate counts cannot be made due to high fiber densities on the sticky tape. For these greater exposures the charged ball count was used. (The charged ball detection system, utilizing two differentially connected charged balls, is the same as that used by NASA and others in their testing programs and is shown in Figure 7.)

Fiber Lengths Selected for Contamination Testing

The fiber lengths selected for contamination testing were 2 mm nominal, 4.3 mm nominal, 9 mm nominal, and 10.8 mm nominal. In addition, combinations of fiber lengths were chopped simultaneously during selected tests. These combinations were 4.3 mm and 9 mm, and 9 mm and 10.8 mm. Each of these nominal lengths and combination of nominal lengths has a fiber length distribution associated with it and these are shown for the 2 mm, 4.3 mm, 9 mm, 10.8 mm, 4.3 mm plus 9 mm, and 9 mm plus 10.8 mm cases in Figures 8 through 13, respectively. Table 2 lists the significant parameters of these different length distributions. The actual fiber release spectrum for an accidental release as postulated by NASA is shown superimposed with the 2 mm fiber length spectrum in Figure 14. The fiber length spectrum for accidentally released fibers lies between that for 2 mm fibers and 4.3 mm fibers. However, the 4.3 mm fiber length distribution contains a far greater number of relatively long fibers than the fiber length distribution for accidentally released fibers. Hence the testing results for 2 mm fibers are, within testing accuracy, deemed the best overall representation of insulator performance under accidental release contamination. For the sake of conservation, an estimate of vulnerability between that for 2 mm and 4.3 mm fibers can be chosen for distribution class insulation vulnerability assessment. A wide range of fiber

lengths and combinations of lengths was chosen to allow determination of the dynamic range and trends of insulator vulnerability to conducting fibers. This allows for a greater understanding of the contamination mechanics and resulting failure modes.

Effects of Weathering

Insulators installed outdoors on a utility distribution system have received a certain amount of weathering. These weathered insulators, though ideal for testing, are difficult to obtain in the numbers and variety necessary to this test program. Clean, new insulators are readily obtainable. In order for clean, new insulator samples to be tested in this program it was necessary to establish that their behavior under carbon/graphite fiber contamination does not differ significantly from that of weathered insulators. Samples of weathered 7.5 kV pin insulators were obtained from a local utility. Samples of new insulators of the same type were purchased from a supplier. Both groups were tested with 9 mm fibers and the results of the test series are shown in Figure 15. It can be seen that there is no statistical differences between the mean exposure to fail at 95 percent confidence level.

Hence, new insulators were used throughout the remainder of the test program as test samples with confidence that their behavior models that expected under field conditions.

TEST RESULTS

The data on exposure to flashover are presented in Table 4 for each test series performed. For uniformity and to facilitate comparisons all data were plotted on Weibull paper for analysis since this distribution provided the best fit. α_0 is the theoretical minimum exposure at which flashover is possible. It is a parameter necessary in making a Weibull curve fit. For these data an $\alpha_0 = 0$ was selected because we can be confident that 0 is a lower limit to flashover exposure and also most of the data fit best when $\alpha_0 = 0$. Each graph indicates the number of tests, the mean and standard deviation of the data, and α and β of the Weibull curve fit.

Confidence Intervals

Established techniques were used in placing confidence intervals about mean flashover exposure of an experiment. Because the data distribution is non-Gaussian, the technique utilized in placing confidence intervals about the mean is the Wilcoxon Signed-Ranks test. A description of this test may be found in the *National Bureau of Standards Handbook 91.*

For each confidence interval about the mean the Wilcoxon Signed-Ranks test is performed twice, once for the upper limit and once for the lower limit. In order to determine the confidence interval, the upper and lower limit must be assumed. After making the assumption, the Wilcoxon test is utilized. If a level of significance, $\alpha = .025$, is obtained then the limit has been found. If the desired level of significance is not obtained then a new assumed value of a limit must be chosen and the test performed again.

Another method of data evaluation discussed by Guttman and Wilkes in *Introductory Engineering Statistics* makes no assumption about the distribution of samples and places a probability

of obtaining a flashover below the lowest observed exposure. This method states that the number of observations required so that the probability is δ that at least $1 - \alpha$ of the distribution will exceed the smallest observation of the sample is given by:

$$n = \frac{\log (1 - \delta)}{\log (1 - \alpha)} \tag{5}$$

From this we can derive the statement that with δ confidence, there is no more than α probability of obtaining a flashover at an exposure below the least observed exposure of n tests or $\alpha = 1 - (1 - \delta)^{1/n}$. Table 3 shows the relationship between the number of tests and the probability of obtaining flashovers below the lowest observed exposure with confidence levels of 85%, 90%, and 95%. This table indicates that a large number of tests is required to establish the lower end of the flashover exposure curve for the confidence level listed. For example, 45 tests are required to establish 90% confidence that no more than 5% of an insulator type would flashover at an exposure less than the minimum observed exposure.

Table 4 summarizes data for all insulators tested. It shows the number of tests, the nominal fiber length of contaminating fibers, exposures, means and standard deviations, confidence limits about the mean exposures, minimum exposures, probability of obtaining an exposure less than the minimum, and the mean fiber concentrations during the experiment.

Short Fiber Tests

As discussed earlier the performance of distribution class insulation contaminated by short (2 mm) fibers is believed to be the most representative of what would be expected in an actual accidental fiber release. Studies have shown that most of the fibers at locations any distance away from the burn site would be short, averaging 2 mm to 2.5 mm. Figure 14 illustrated the fiber length distribution postulated by NASA for an accidental release superimposed on the 2 mm fiber length distribution used for the 2 mm tests in this report. The tests performed with 2 mm fibers indicate mean flashover exposures of approximately 10^8 fiber-sec/m^3 for distribution class insulation.

2 mm and 4.3 mm test data are found in Table 4. Only a limited quantity of 2 mm fiber test data are available because of the extended time required to complete each test.

Wet Tests

Wet insulation tests were conducted with 2 mm fibers to simulate actual fiber releases under heavy fog conditions. Insulator surfaces were wetted continuously during the tests by vapor condensing as it passed over the surfaces. The insulator was contaminated with airborne contamination. Wet surfaces were found to decrease the exposure required for flashover. There was great variability in the degree that wet testing lowered mean exposure to flashover. The 15-kV distribution post insulator test results showed only a slight decrease in exposure to flashover while the 7.5-kV pin insulator test results showed a great decrease in exposure to flashover. This can be seen in Table 4. Fibers show a greater tendency to stick to wet insulator surfaces than dry, lowering the exposure required to induce flashover. Also, the rising steam carries fibers up over the surface, contaminating lower surfaces which are normally shielded. The wet fibers tend to stick together in

strings which align in the direction of the voltage gradients. This may also decrease flashover exposure. The wet tests give more consistent results than dry tests with less variability of data. For wet tests $\sigma/\mu \approx 25\%$ was obtained as compared to $\sigma/\mu \approx 50\%$ for dry tests. The severity of contamination of an insulator, wet from condensate, is usually greater than of one wet from pouring rain because running water over the insulator's surface would clean the insulator.

Long Fiber Tests

Test series with longer fibers had the advantage of being performed quickly since failures occur at much lower exposures. The data were also more consistent so these tests were better used to show trends in the data. The disadvantage is that in actual release situations very few long fibers are released, therefore long fiber tests are not representative of actual releases as predicted by NASA.

The usefulness of long fiber tests lies in application of trends discovered to predict data for more difficult tests such as short fiber or higher voltage tests. In many cases trends are indicated but not enough data exists to substantiate them. The next section discusses trends observed in the data.

ANALYSIS OF RESULTS

Test results were examined to determine the effects of fiber length, concentration, and voltage class on exposure to flashover of distribution class insulation. The effect of an accidental release on an actual power distribution system is reviewed.

The Effect of Fiber Length on Exposure to Flashover

Tests were performed on selected insulator specimens using several different fiber lengths. Mean exposure to flashover was determined at each length. Tests at several fiber lengths indicate an exponential relationship between mean fiber length ℓ and mean exposure to flashover E. E was found to be proportional to $e^{k\ell}$. The curves shown in Figure 16 indicate this trend in the data. The mean fiber length for tests with multiple fiber lengths also fits the exponential exposure curve as shown in the same figure.

The objective of the multiple fiber length tests was to determine the effect of irregular fiber length distributions on exposure to flashover. Test results indicate that even for unusual length distributions the mean fiber length can be used to obtain an approximation of flashover exposure.

Test time could be reduced if data from tests with long fibers could be extrapolated to the shorter fibers that would actually be released. As Figure 16 indicates, results of 9 mm and 10.8 mm test data could be used to indicate the results of 2 mm tests but the exposure to flashover predicted could be very inaccurate. For example, the results of actual tests on a 7.5 kV pin with 2 mm fibers indicate a mean flashover exposure of 2.8×10^8 but a flashover at over 10^{10} would have been predicted if only a line drawn through the 9 and 10.8 mm test data had been used.

To obtain a reasonably accurate prediction of short fiber flashover exposures, tests should be performed with at least three different longer fiber lengths such as 12, 8, and 4 mm.

The Effect of Fiber Concentration on Exposure to Flashover

The fiber concentration for the test series was somewhat controllable by varying the speed of the fiber chopper driving motor and by varying air flow through the dispersal chamber. Measured average concentrations vary as much as 3 to 1 during a given test series with test conditions unchanged. This is due to fiber clumping in the dispersal chamber, occasional chopper plugging, measurement inaccuracy, and the random nature of the phenomenon.

The concentration given for each test series in Table 4 represents the average over all the series test times. This average is determined by:

$$\text{Concentration} = \frac{\Sigma \text{ exposure}}{\Sigma \text{ test time}} \qquad (6)$$

Preliminary tests with long fibers indicate that lowering concentration levels tends to increase mean flashover exposures. This phenomenon was observed when accidental increases in concentration precipitated a flashover on several occasions. Although a limited number of tests indicate there is an effect, more tests are needed for quantification of this effect. Figures 17, 18, and 19 show the effect on test results of varying the concentration. Since concentrations expected in an accidental fiber release at any distance away from the release point are less than those used for testing, the test results of exposure to flashover may be conservative. Current predictions for an actual release indicate fiber concentrations of approximately 100 fibers per cubic meter may be expected.

The longer fiber length tests indicated a possible effect on concentration, but no pronounced concentration effect was observed during short fiber tests. Test concentrations for the short fiber tests were maintained at over 10^4 in an effort to shorten test times. No short fiber tests were made at lesser concentrations to determine the effect of concentration. All indications are that breakdown of test specimens is a fiber deposition related surface phenomenon even though concentrations are high. Although variations in flashover exposure with concentration were observed, no evidence of air breakdown was noted.

The Effect of Voltage Class on Exposure to Flashover

Tests on a given type of insulator indicate that mean exposure to flashover decreases as insulator rated voltage increases. The 9 and 10.8 mm data on pin cap insulators, transformer bushings, and distribution post insulators shown in Table 4 indicate this trend. This trend may not be applicable to station class insulation. It is hoped that future tests will clarify this trend.

Other Trends

Station insulation is designed with much larger creepage distances than is line insulation. As would be expected, station insulation is much more resistant to carbon fiber contamination. The exposure required to cause flashover for station insulation is so high that testing even with long fibers is very time consuming.

The mean exposure to flashover for insulators mounted vertically is lower than for the same insulators mounted horizontally in most cases. This trend is indicated in Table 4 by the data for 9 mm fiber lengths on the 15 kV distribution post and the 7.5 kV station post. The data on the 5 kV transformer bushing is not consistent with this trend. Since it is a spin top bushing different results are expected. For a spin top bushing the top electrode is enclosed and covered. There are holes in the sides around the high voltage electrode for wire entrance. When the 5 kV bushing is mounted vertically the fibers are better shielded from the more critical insulation near the high voltage conductor.

Another trend observed is that insulators with similar geometry have similar mean exposures to flashover as well as similar flashover probability distributions. For example, the 15 kV transformer bushing gives results very similar to the 15 kV distribution post. This is probably because insulator shapes and creepage distances are similar. The transformer bushing creepage is 28 cm while the distribution post creepage is 25 cm and the transformer bushing dry arcing distance is 17 cm while the distribution post dry arcing distance is 15 cm. There are 5 sheds on the transformer bushing and only 3 on the distribution post. The transformer bushing sheds are closer together which could offset the greater creepage distance since fibers are long enough to bridge some of the creepage distance.

EFFECTS OF CARBON FIBER CONTAMINATION ON POWER DISTRIBUTION SYSTEMS

Portions of the actual power distribution systems surrounding selected major airports are being evaluated by NASA to determine the degree of hazard posed by a worst-case accidental fiber release. Technical information on the types and number of insulators in the areas immediately surrounding the selected airports was obtained by NASA from the electric utility companies serving these areas. This information was used in conjunction with the Waltz Mill chamber test data on distribution class insulation to evaluate the vulnerability of the power distribution systems. The vulnerability calculations were performed by NASA in conjunction with the development of the computerized risk models.

The carbon fiber exposures predicted by the NASA fiber release models indicate a worst case of about 10^5 fiber-seconds/m^3 with the vast majority of releases less than 10^3 fiber-seconds/m^3. The areas of maximum exposure involved in these worst case scenarios are on the order of one square kilometer. These areas of high exposure are small and the worst case exposures are 3 to 5 orders of magnitude below the mean exposure required to fail distribution class insulation with 2 mm fibers. The probability of inducing extensive insulation failures was shown to be negligible. The outage incidence due to accidental carbon fiber releases is insignificant when compared to the current distribution system outage rates normally experienced by these electric utilities due to such occurrences as lightning, tree contact, vehicular damage, etc. The NASA calculations were performed to verify this. Results of these calculations were presented earlier.(1)

SLURRY DEVELOPMENT

The purpose of the slurry development and the efforts to discover trends relating voltage to flashover exposure is to allow testing of transmission class insulation without the use of an airborne contamination test chamber. The objective is to develop a technique for performing these

tests "synthetically". Work was performed on the development of a slurry testing technique to supplant airborne fiber testing in a contamination chamber. It was found that:

1. Shorter fibers do not clump as easily in the slurry. The question remaining is whether 2 or 4.3 mm fiber is better for testing.

2. Resistance measurements do not work in determining how many fibers are in the slurry.

3. A binder or thickening agent is needed in the slurry to keep fibers on the insulator surface. A wetting agent alone was utilized and too many fibers slid off the surface.

Two things are required for a slurry to be useful. First, a requirement of a useful slurry is a method of correlating results to make them meaningful in the case of an actual airborne contamination problem. Results can be correlated by using a standard slurry which flashes near the operating voltage of an insulator and then comparing other insulators by determining the voltage at which they flash. Another way of correlating results is always testing at rated voltage and varying slurry fiber density to obtain flashover at the rated voltage.

Varying the voltage is more useful because it is more easily and quickly done. The greatest value of a slurry is in allowing relative comparisons between insulators. It is doubtful that direct correlation could be made between slurry and airborne contamination in all circumstances.

A second requirement is a method of measuring fiber density in the slurry. One possible solution to this problem is to measure the fibers put into the slurry by weight. Otherwise, expensive particle counters set up to count particles in a suspension could be utilized. To verify the applicability of determining fiber density by fiber weight measurements, work needs to be performed to determine if water evaporation or insulator dipping would cause appreciable changes in slurry fiber density.

The slurry can be used either dry or wet. The following points should be considered when deciding whether it is better wet or dry. The wet slurry allows more rapid testing and less delay because there is no wait for insulators to dry. However, results are not so reproducible if insulators are tested wet because they need to be handled to be mounted. Also, the uneven drying caused by leakage currents heating the surface during testing could change flashover characteristics.

The dried slurry binds fibers so no change in orientation occurs during testing. When the dry slurry was tried some of the fibers on the insulator surfaces jumped out of the binder and off the surface. A dried slurry would allow multiple dipping which would be convenient for increasing fiber deposition on the insulator surfaces.

To enable correlation of deposition on insulators at flashover to slurry depositions, qualitative deposition measurements were made. This was done for the airborne tests by sticking transparent tape on contaminated insulator surfaces and using it to lift the fibers. The tape was preserved by placing it on white paper. The fiber does not deposit evenly over insulator surfaces. For short fiber tests upper surfaces have fibers piled up before lower surfaces are contaminated enough to cause flashover.

Further development of slurry techniques will enable an investigation of binders to be used for the slurry. One is Metylan wallpaper paste. The other is Cab-o-Sil, a pyrogenic silica. Preliminary testing was done using a Metylan slurry. Best results were obtained with approximately 13 grams of Metylan per liter of water. Flashover of a 7.5 kV pin insulator occurred near rated voltage

when the insulator was dipped, allowed to dry, dipped again in a solution with 1.4 gms of fiber per liter of solution, and allowed to dry again. A selection of fiber length, binder, and the test method will be made as future work.

Work to be Performed in the Future

- Continue slurry development and evaluation of transmission class insulation vulnerability.
- The power supply will be uprated to 40 kV line-to-ground.
- Investigate power supply requirements for DC testing.
- Data analysis will be continued and tests made to better establish observed trends.
- Limited testing will be performed with air flow across insulator surfaces to examine the effects of wind on flashover characteristics.

VULNERABILITY OF NUCLEAR, FOSSIL, AND HYDRO GENERATING PLANTS TO CARBON/GRAPHITE FIBER INDUCED OUTAGES

This study evaluated the ability of power generating stations to maintain normal power generation when the surrounding environment is contaminated by an accidental carbon fiber release. Loss of non-essential equipment is not considered critical since loss of the plant does not result. The vulnerability assessment included only the power plant generating equipment and its associated controls, instrumentation, and auxiliary and support systems. It specifically excludes exposed outdoor high voltage substations, but includes the substation's controls. The outdoor substation high voltage equipment is being evaluated separately using insulation failure data determined under Phase II of this project.

This study includes the following types of power plants:

- Nuclear power plants
- Coal fired power plants
- Oil and gas fired power plants
- Hydroelectric power plants
- Gas turbine-generators.

Investigative Methodology

During NASA investigations into the vulnerability of civil aircraft to carbon fiber release it became apparent that detailed testing of every item in the aircraft was not necessary. This was because not all components are critical and only a certain few are likely to be both critical and highly vulnerable. The analysis procedure involves identifying the critical systems and selecting items from these systems for tests based on an engineering evaluation of vulnerability using test data on generically similar or related components. It has been demonstrated that reasonably accurate es-

timates of carbon fiber vulnerability can be made for items on which test data on generically similar items is available. These generic classes of equipment include such things as TTL logic on PC boards-coated/uncoated, terminal strips – .64-cm (1/4-in) spacing, cabinets with top and bottom louvers – natural circulation, etc. This approach has been adopted for estimating the vulnerability of the control systems in power plants and substations.

The investigation of power plants and substation vulnerability proceeded along the following lines:

1. Detailed discussions were held with Gibbs & Hill, Inc. to obtain the design details of nuclear and fossil fired power plants. The designs of typical plants were reviewed for vulnerability to fiber penetration regarding outside air entrance points, air filtering, plant internal heating, ventillation and air conditioning, and control room air supplies. Using this information, along with transfer function test results for commercial air filters, carbon/graphite fiber transfer functions were determined with assistance from NASA for the numerous functional areas of each type of power plant. This permits an evaluation of expected fiber exposures to equipment in these areas.

2. From these design drawings of typical power plants, and from power equipment manufacturer's technical literature lists have been compiled of the generic types of equipment in the different functional areas in the power plants under consideration.

3. These lists were refined to identify only the critical functions and equipment in each type of power plant.

4. Existing test data on generically similar types of equipment, or on related equipment if available, has been assembled. This is used in light of vulnerability testing experience and engineering judgement based on the generic classes of components present to assess the vulnerability of the individual critical components.

5. Each type of power plant was then evaluated in light of expected release scenarios to determine its vulnerability to carbon fiber releases.

6. The vulnerability analysis of substation controls proceeded along similar lines with typical substation control layouts, building details, air filter data, and technical information on equipment having been obtained. The vulnerability analysis relative to critical components also proceeded in a similar manner.

STATUS AND RESULTS OF INVESTIGATION

During the course of the investigation it became apparent that the area transfer functions for fossil fired plants were essentially the same for corresponding plant areas regardless of the plant fuel type. In other words the functional area transfer functions are equivalent for corresponding areas of coal fired, gas fired, and oil fired power plants. The area transfer functions calculated for these plant types are applied to all the generic fossil fuel-fired power plants considered in the analysis.

It also became apparent that the control equipment located in these plants is generically equivalent regardless of the type of plant. For example, a control computer can be expected to have the same vulnerability to carbon/graphite fibers regardless of the type of plant it is located in. This same principle applies to other typical power plant and substation control equipment.

Table 5 itemizes the functional areas for the generic power plants and substations under consideration. It also shows:

- The type of air filter typically utilized for air filtration in each functional plant area.
- ASHRAE dust spot efficiency for the filters above (conservative) and filter transfer function.
- Volume and floor area for each functional area in each plant (typical).
- Air infiltration and circulation rates.
- The calculated area carbon/graphite fiber transfer function for each area.
- The expected range for typical and worst case carbon/graphite exposures to equipment located inside each area.
- The assessed or estimated mean exposure to fail for the most sensitive component in each area.

It can be seen from Table 5 that the mean exposure required to fail the most sensitive critical component in each area is several orders of magnitude greater than the worst exposure it is expected to ever receive. The probability of inducing a failure in a component under these conditions is extremely small. The equation below is used to calculate the probability of component failure, P_f, due to carbon/graphite fiber contamination.

$$P_f = 1 - e^{-\frac{E}{\bar{E}}} \tag{7}$$

It can be seen that this probability of failure, for the expected exposures, is on the order of 10^{-5} to 10^{-7} during any given exposure incident. However, these components generally have an inherently much higher probability of failure in any given year of normal service due to malfunctions other than those likely to be induced by carbon/graphite exposures. These "routine" malfunctions during normal service, and the resulting outage of the particular item involved, are generally compensated for through redundancy of this critical equipment at the time of plant design and construction. In addition, most automatic control systems, besides redundancy, may allow for a manual mode of operation in the event of unit failure. Through this redundancy of design and the extremely low probability of a carbon/graphite fiber induced failure, it is concluded that accidental releases of carbon/graphite fibers do not pose any unusual hazard to power plant and substation control systems.

TABLE 1.- INSULATOR DESCRIPTION AND MANUFACTURER

DESCRIPTION	MANUFACTURER	TYPE NUMBER
7.5 kV Pin	Ohio Brass Company	9953
15 kV Pin	Ohio Brass Company	37715
5 kV Transformer Bushing	Westinghouse Transformer Plant	773C902C02
15 kV Transformer Bushing	Westinghouse Transformer Plant	772C078G03
34.5 kV Transformer Bushing	Westinghouse Transformer Plant	772C078G13
7.5 kV Suspension Insulator	NGK – Locke	16583
7.5 kV Station Post	Lapp	73631-70
10 kV Suspension Insulator	Lapp	8200-70
34.5 kV Station Post	Lapp	73634-70
15 kV Distribution Post Insulator	Lapp	4415-70
15 kV Horizontal Distribution Post	Lapp	74115-70
34.5 kV Distribution Post	Lapp	9435-70

TABLE 2.- FIBER LENGTH

Nominal Length	μ (Mean) mm	u (Mode) mm	σ (Standard Deviation) mm
2	2.06	2.06	.67
4.3	4.3	4.1	.51
4.3 + 9	5.0	4.0	2.1
9	9.0	8.6	.74
9 + 10.8	9.2	9.8	1.4
10.8	10.8	11.8	2.7

TABLE 3.- PERCENT OF INSULATORS (α) THAT WILL FAIL AT AN

EXPOSURE OF LESS THAN MINIMUM SAMPLE

Number of Tests	Confidence Level (δ)		
	85%	90%	95%
1	85%	90%	95%
2	61%	68%	78%
3	47%	54%	63%
4	38%	44%	53%
5	32%	37%	45%
6	27%	32%	39%
7	24%	28%	35%
8	21%	25%	31%
9	19%	23%	28%
10	17%	21%	26%
11	16%	19%	24%
12	15%	17%	22%
13	14%	16%	21%
14	13%	15%	19%
15	12%	14%	18%
16	11%	13%	17%
17	11%	13%	16%
18	10%	12%	15%
19	10%	11%	15%
20	9%	11%	14%
21	9%	10%	13%
22	8%	10%	13%
23	8%	10%	12%
24	8%	9%	12%
25	7%	9%	11%
26	7%	8%	11%
27	7%	8%	11%
28	7%	8%	10%
29	6%	8%	10%

TABLE 4.- COMPILATION OF RESULTS OF TESTS ON INSULATOR SPECIMENS

Insulator	n	Fiber Length mm	Exposure μ	Exposure σ	Confidence Interval About Mean 95%	Minimum Exposure	P<min*	Concentration Mean
7.5 kV Pin	4	2.0	2.8×10^8	1.3×10^8		1.4×10^8	44%	1.6×10^4
7.5 kV Pin (Wet)	7	2.0	5.8×10^7	2.0×10^7	$3.4 \times 10^7 < \mu < 7.4 \times 10^7$	4.8×10^7	28%	1.5×10^4
15 kV C-Neck D. Post Vert	2	2.0	7.3×10^7	3.0×10^7		5.2×10^7	68%	1.6×10^4
15 kV C-Neck D. Post (Wet)	10	2.0	6.2×10^7	1.0×10^7		4.7×10^7	21%	1.6×10^4
34.5 kV D. Post Vert	5	2.0	1.8×10^8	$.9 \times 10^8$		1.53×10^8	37%	1.8×10^4
7.5 kV Pin	46	4.3	4.1×10^7	4.0×10^7	$2.6 \times 10^7 < \mu < 5.7 \times 10^7$	2.8×10^7	5%	1.3×10^4
7.5 kV Stat. Post Vert	1	4.3	$>4.0 \times 10^8$					1.5×10^4**
7.5 kV Stat. Post Hor.	1	4.3	4.0×10^8					2.1×10^4
7.5 kV Pin	15	4.3 + 9	1.7×10^7	7.6×10^6	$1.3 \times 10^7 < \mu < 2.3 \times 10^7$	3.0×10^6	14%	8.3×10^3
15 kV C-Neck D. Post Vert	26	4.3 + 9	2.9×10^6	2.6×10^6	$2.0 \times 10^6 < \mu < 3.0 \times 10^6$	8.7×10^5	8%	6.7×10^3
7.5 kV Pin	52	9.0	4.8×10^6	2.9×10^6	$3.7 \times 10^6 < \mu < 5.3 \times 10^7$	1.6×10^6	6%	5.0×10^3
15 kV Pin Cap	14	9.0	2.1×10^6	5.9×10^5		1.3×10^6	15%	2.5×10^3
7.5 kV Stat. Post Vert	10	9.0	1.2×10^7	1.2×10^7	$4.3 \times 10^6 < \mu < 2.47 \times 10^7$	1.6×10^6	21%	4.3×10^3
7.5 kV Stat. Post Hor.	5	9.0	3.4×10^7	2.3×10^7		1.2×10^7	37%	6.9×10^3
34.5 kV Stat. Post Vert.	9	9.0	4.9×10^7	4.7×10^7		1.3×10^6	23%	12.2×10^3
5 kV Fostoria Insulator	4	9.0	8.4×10^6	6.6×10^6		2.9×10^6	44%	2.0×10^3
5 kV Trans. Bushing Vert.	5	9.0	3.8×10^6	7.9×10^5		7.5×10^6	37%	1.2×10^3
5 kV Trans. Bushing Hor.	6	9.0	2.3×10^6	7.1×10^5		1.3×10^6	32%	1.0×10^3

TABLE 4.- Concluded

Insulator	n	Fiber Length mm	Exposure μ	Exposure σ	Confidence Interval About Mean 95%	Minimum Exposure	P<min*	Concentration Mean
15 kV Trans. Bushing Vert.	16	9.0	1.0×10^6	3.3×10^5		6.0×10^5	13%	1.3×10^3
15 kV C-Neck D. Post Vert.	15	9.0	1.2×10^6	4.0×10^5	$9.0 \times 10^5 < \mu < 1.4 \times 10^6$	5.6×10^5	14%	1.2×10^3
15 kV C-Neck D. Post Hor.	15	9.0	1.8×10^6	6.0×10^5		5.6×10^5	14%	1.6×10^3
34.5 kV D. Post Vert.	18	9.0	9.5×10^5	6.4×10^5	$5.1 \times 10^5 < \mu < 1.3 \times 10^6$	3.0×10^5	12%	9.2×10^2
7.5 kV Suspension Vert.	13	9.0	7.9×10^6	4.8×10^6		2.7×10^6	16%	2.9×10^3
7.5 kV Pin	17	9.0+10.8	5.0×10^6	3.2×10^6	$3.3 \times 10^6 < \mu < 6.5 \times 10^6$	2.3×10^6	13%	4.5×10^3
34.5 kV D. Post Vert.	15	9.0+10.8	8.0×10^5	2.8×10^5	$6.4 \times 10^5 < \mu < 9.8 \times 10^5$	3.0×10^5	14%	1.1×10^3
7.5 kV Pin	15	10.8	6.5×10^5	2.4×10^5	$5.1 \times 10^5 < \mu < 7.8 \times 10^5$	2.6×10^5	14%	8.6×10^2
7.5 kV Stat. Post Vert.	20	10.8	4.5×10^6	4.3×10^6	$2.35 \times 10^6 < \mu < 4.7 \times 10^6$	1.2×10^6	11%	4.6×10^3
15 kV C-Neck Dist. Post Vert.	15	10.8	5.2×10^5	3.18×10^5	$3.5 \times 10^5 < \mu < 6.2 \times 10^5$	2.4×10^5	14%	6.3×10^2
34.5 kV Dist. Post	16	10.8	2.2×10^5	1.2×10^5	$1.5 \times 10^5 < \mu < 2.7 \times 10^5$	1.5×10^5	13%	5.2×10^2

* *Likelihood of a flashover to occur at an exposure of less than the minimum observed exposure, with 90% confidence.*

** *This insulator flashed only after given exposure and twice rated voltage.*

TABLE 5.- SUMMARY OF TRANSFER FUNCTION DATA, POWER GENERATION LOCATIONS

LOCATION	FILTER TYPE	FILTER DS/RATE	FILTER TF	AREA m^2	VOLUME m^3	AIR FLOW RATES Q_i m^3/sec	AIR FLOW RATES Q_{AC} m^3/sec	AREA TRANSFER FUNCTION	AREA EXPOSURE TYPICAL/WORST CASE	$\overline{E}$ OF MOST SENSITIVE COMPONENT
A. NUCLEAR PLANTS										
1. Control Room										
A. Open	Roll	25%	$8x10^{-3}$	1419	8637	1.92/1.44	17.24/12.95	$3.45x10^{-4}/2.70x10^{-4}$	.27/3.5	10^6 Digital Equip.
B. Closed	HEPA	99.8	10-6	1419	8637		19.19/14.39	0	0	10^6 Digital Equip.
2. Diesel Area	Mesh	0	0.27	495	7561	42		0.218	218/2180	10^7 Diesel Elec. Sys.
3. Unc. Access Area	Roll	25%	$8x10^{-3}$	3149	68252	379		$6.86x10^{-3}$	7/69	10^6 PC Boards
4. Safeguards	Roll	25%	$8x10^{-3}$	764	18068	75.26/50.19		$6.64x10^{-3}/6.13x10^{-3}$	6/66	10^6 PC Boards
5. Fuel Handling	Roll	25%	$8x10^{-3}$	1215	37949	158/105		$6.93x10^{-3}/6.44x10^{-3}$	6/69	10^7 Relays & Cont.
6. Controlled Access	Roll	25%	$8x10^{-3}$	3747	76465	318/212		$6.47x10^{-3}/5.91x10^{-3}$	6/65	10^6 PC Bds./Digital
7. Electrical Bldg.	Roll	25%	$8x10^{-3}$	874	21325	88.8/59.2		$6.68x10^{-3}/6.17x10^{-3}$	6/67	10^7 Elec. Cont./Swgr.
8. Containment	Roll	25%	$8x10^{-3}$	950	99122	413/275		$7.64x10^{-3}/7.48x10^{-3}$	7/76	10^8 Pwr. Pnls. (Enclosed)
9. Turbine Gen.	Mesh	0	0.27	3907	129595	719		0.244	244/2440	10^8 Swgr./Elec. Pnls.
B. FOSSILE FUELED										
1. Control Room	Roll	25%	$8x10^{-3}$	641	11724	2.60/1.95	23.4/17.58	$5.38x10^{-4}/4.84x10^{-4}$	.5/5	10^6 Digital Equip.
2. Electrical Areas	Roll	25%	$8x10^{-3}$	576	18436	76.81/51.21		$6.97x10^{-3}/6.53x10^{-3}$	7/70	$10^6/10^7$ Electronic Cont.
3. Turbine Gen.	Mesh	0	0.27	2604	86377	479		$7.21x10^{-3}$	7/72	10^7 Elec. Swgr. & Cont.
4. Boiler Area	Mesh	0	0.27	1371	97819	543		$7.61x10^{-3}$	8/76	$10^7/10^9$ Controls
C. UNDERGROUND HYDRO	Roll	25%	$8x10^{-3}$	5576	101954	56.6	226	$1.154x10^{-3}$	1.2/12	10^6 Digital Equip.

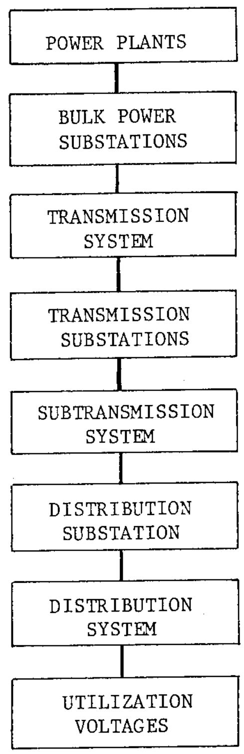

Figure 1.- Basic elements of a power system.

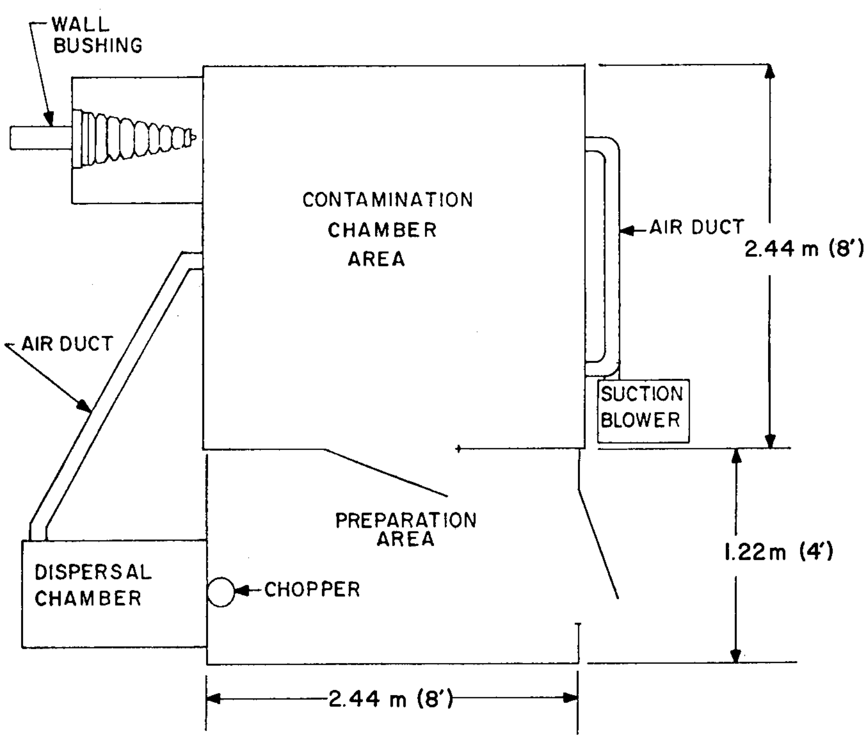

Figure 2.- Contamination system floor plan.

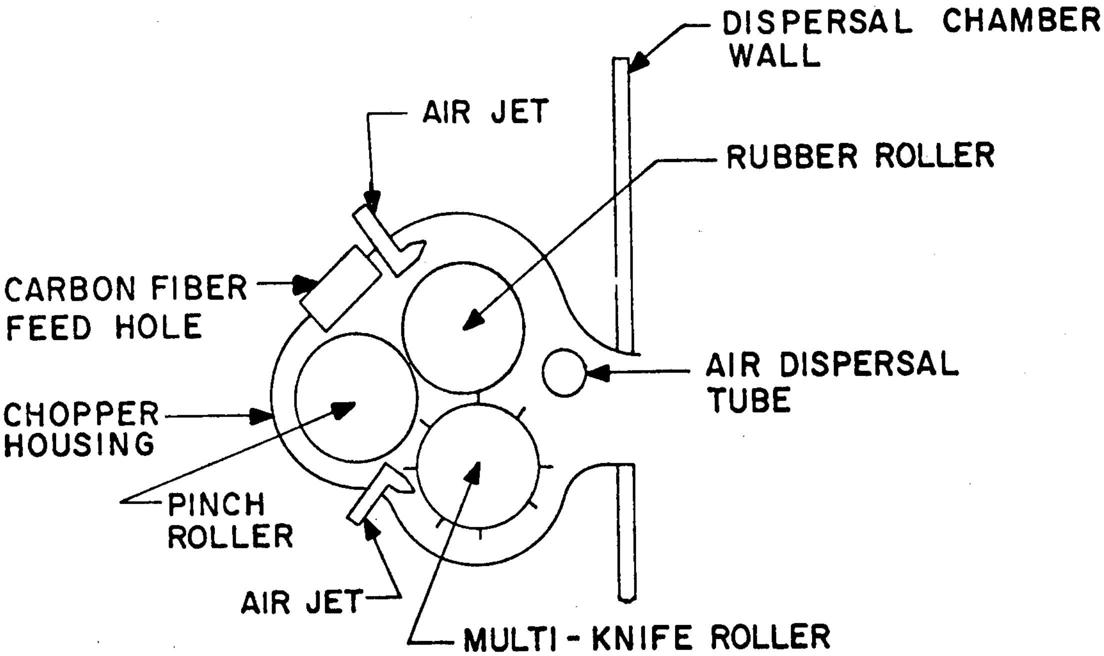

Figure 3.- Multi-knife carbon fiber chopper.

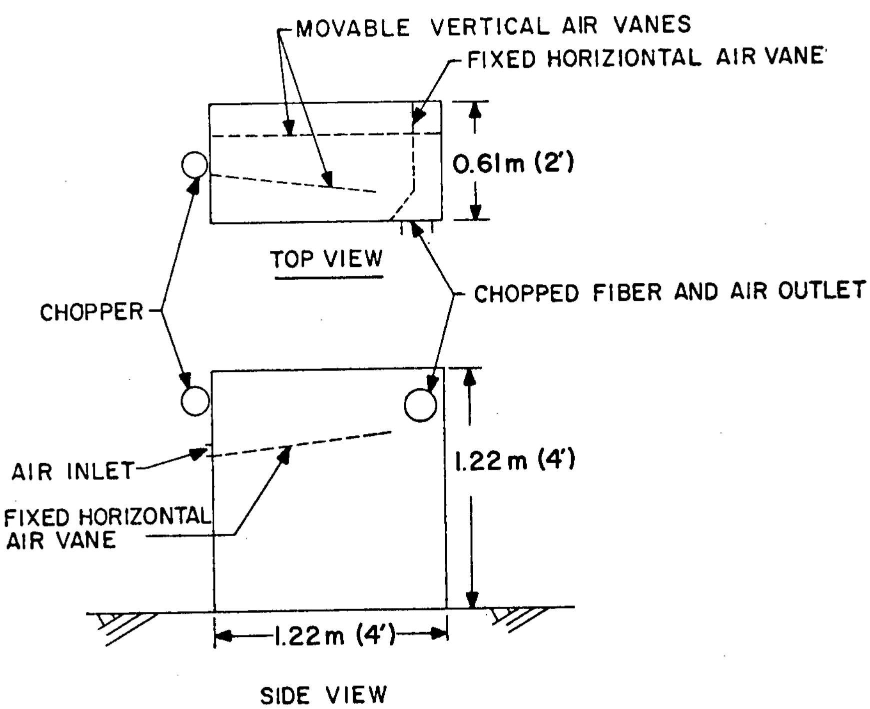

Figure 4.- Dispersal chamber.

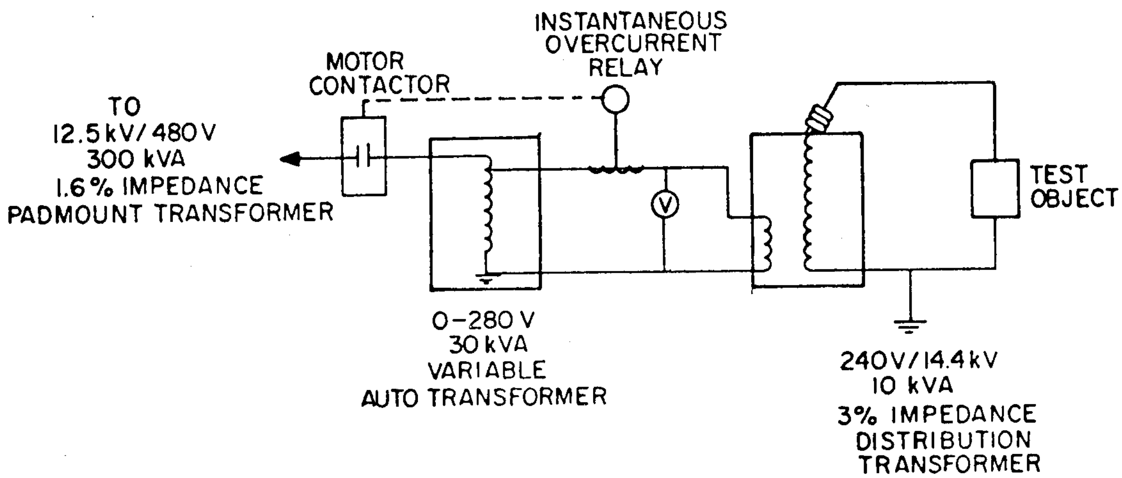

Figure 5.- High voltage supply for 4 kV to 15 kV.

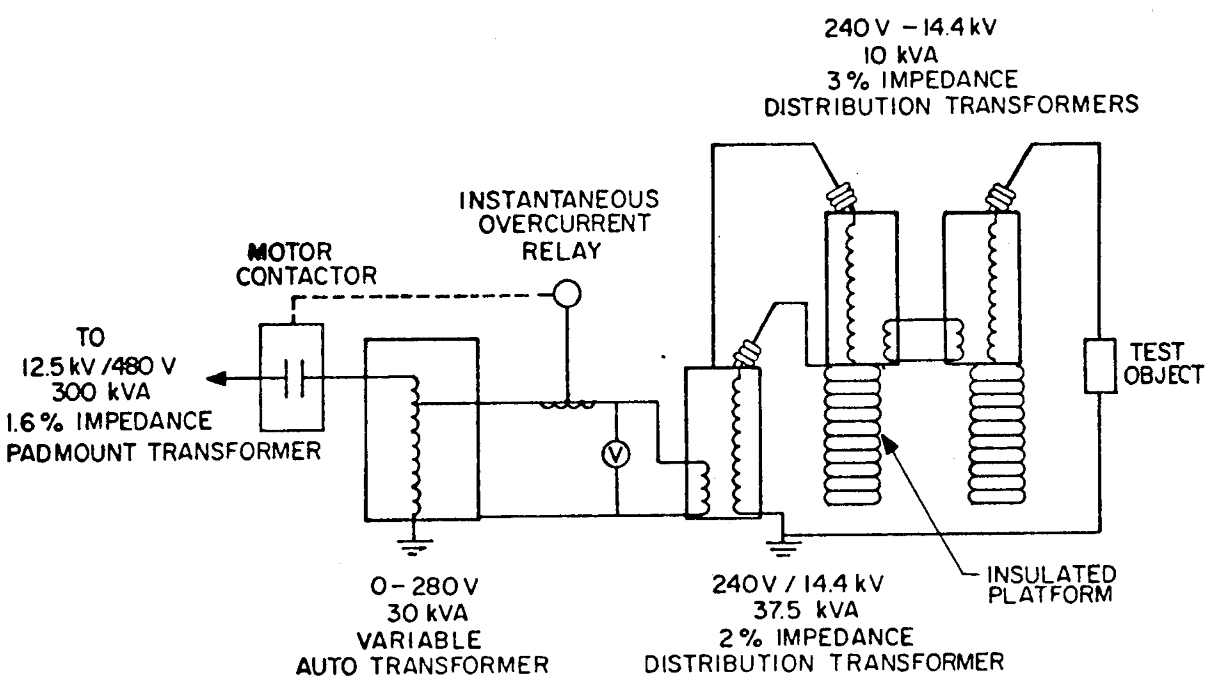

Figure 6.- High voltage supply for 15 kV to 30 kV.

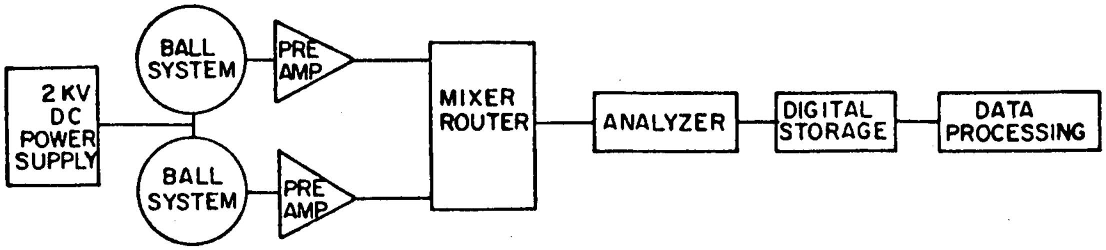

Figure 7.- Fiber counting instrumentation.

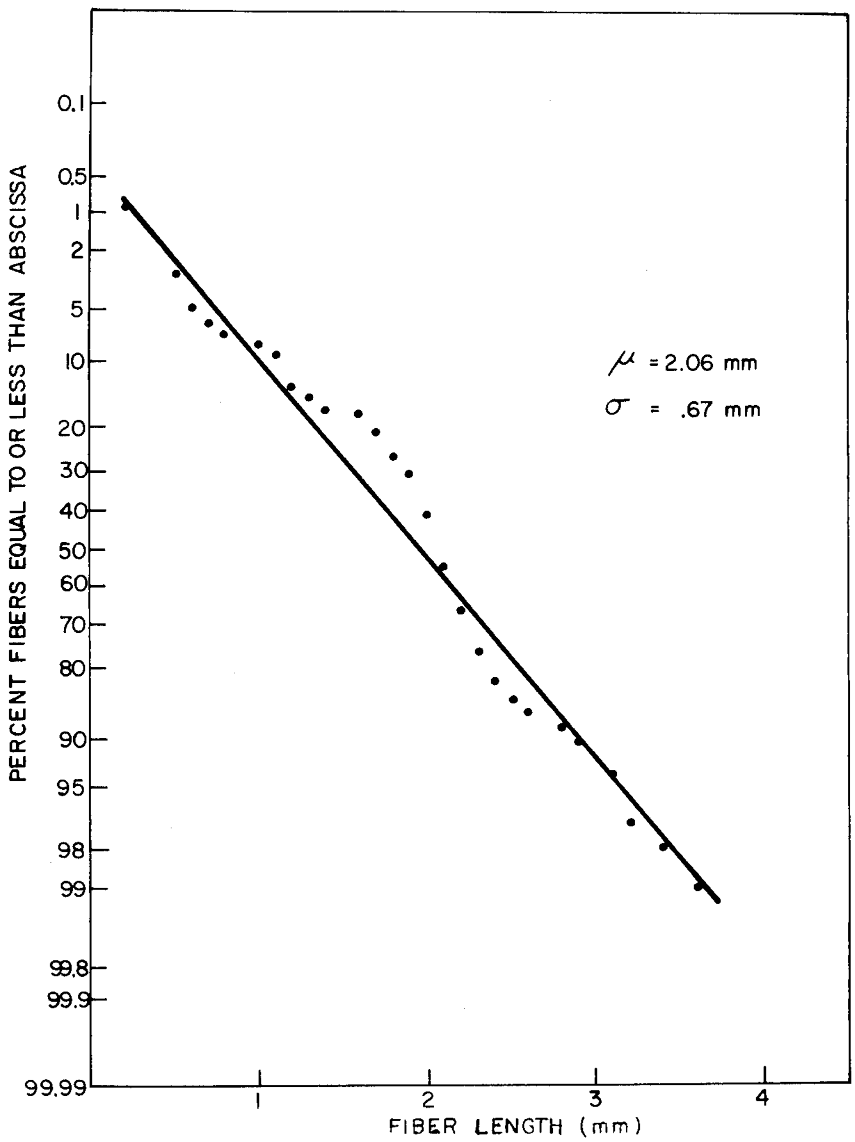

Figure 8.- The 2 mm fiber length distribution plotted on normal probability paper.

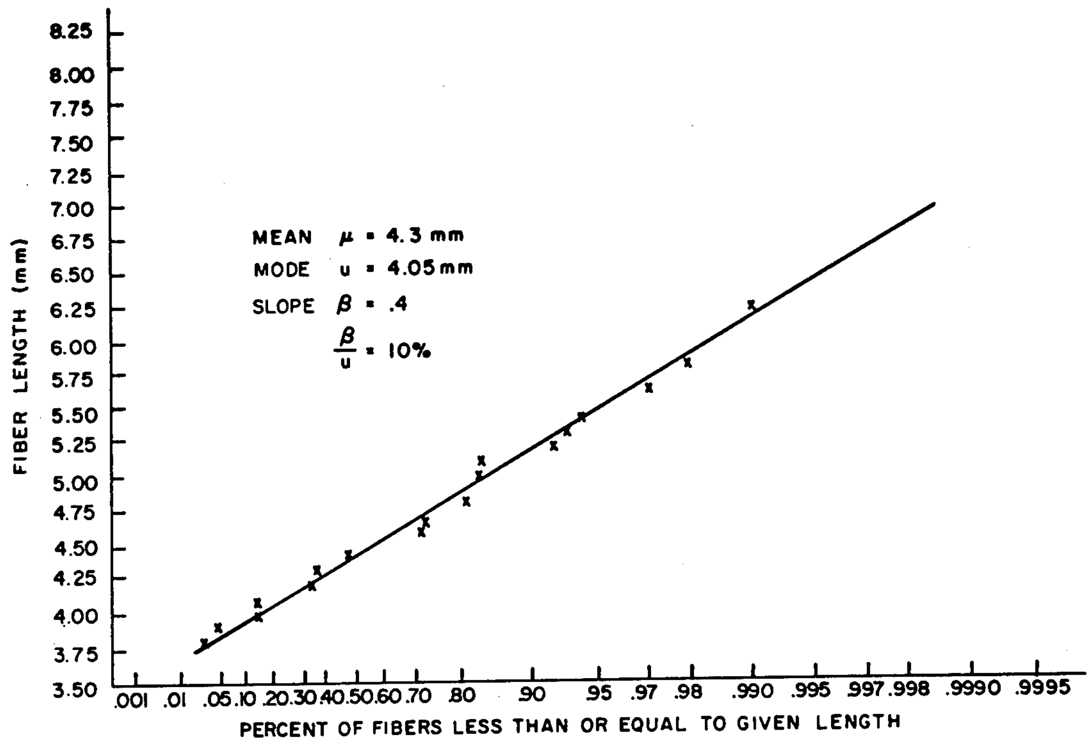

Figure 9.- 4.3 mm fiber length distribution.

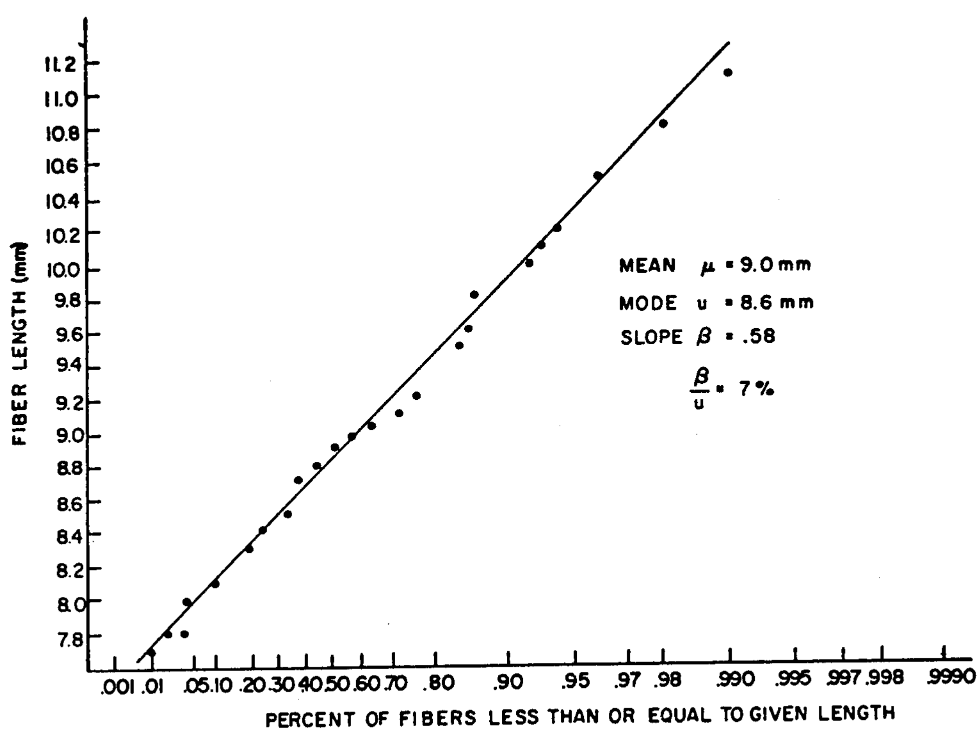

Figure 10.- 9 mm fiber length distribution.

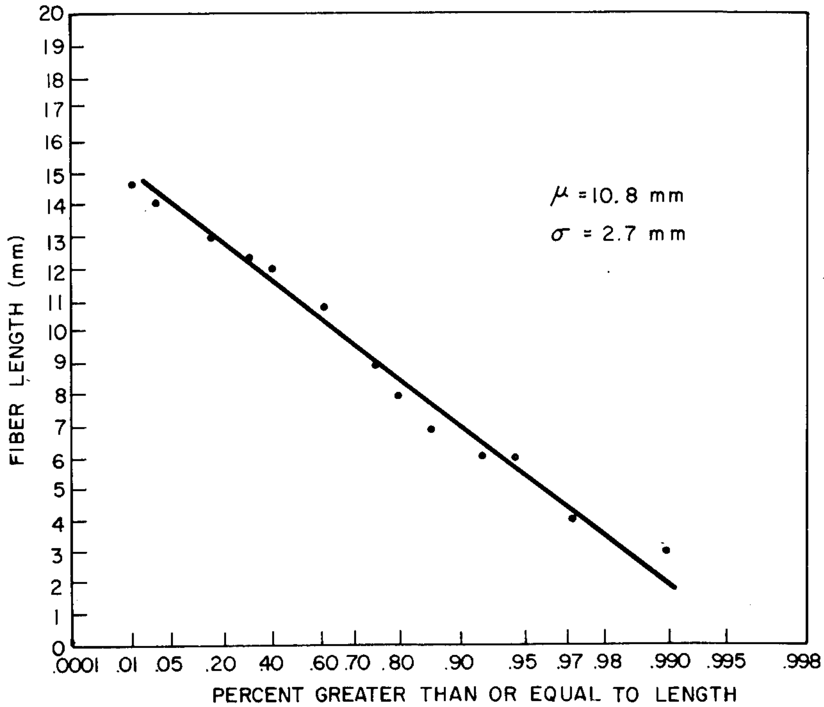

Figure 11.- The fiber length spectrum for 10.8 mm fibers plotted on extreme value paper.

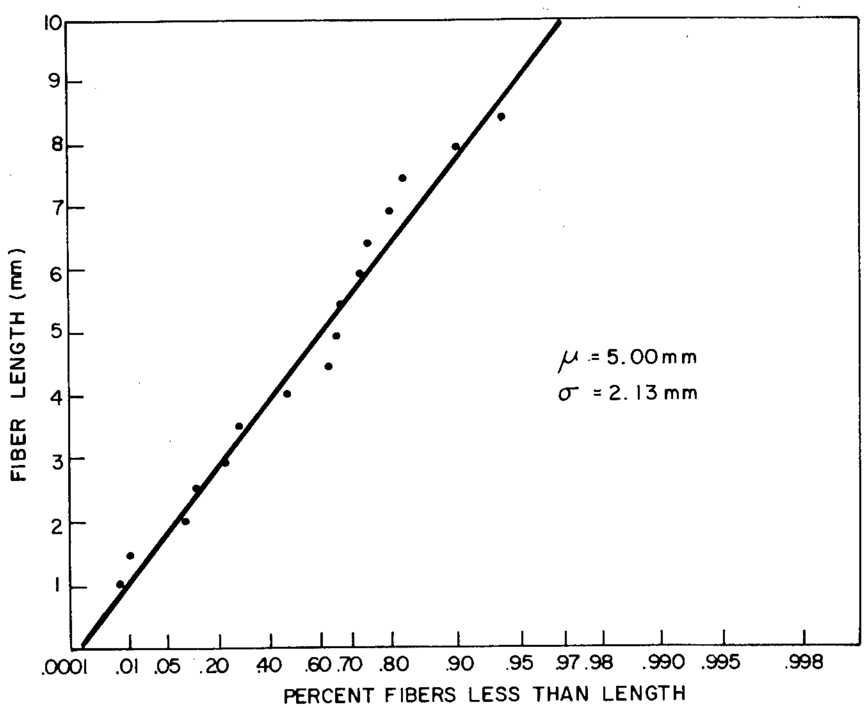

Figure 12.- The fiber length spectrum for 4.3 and 9 mm fibers combined, plotted on extreme value paper.

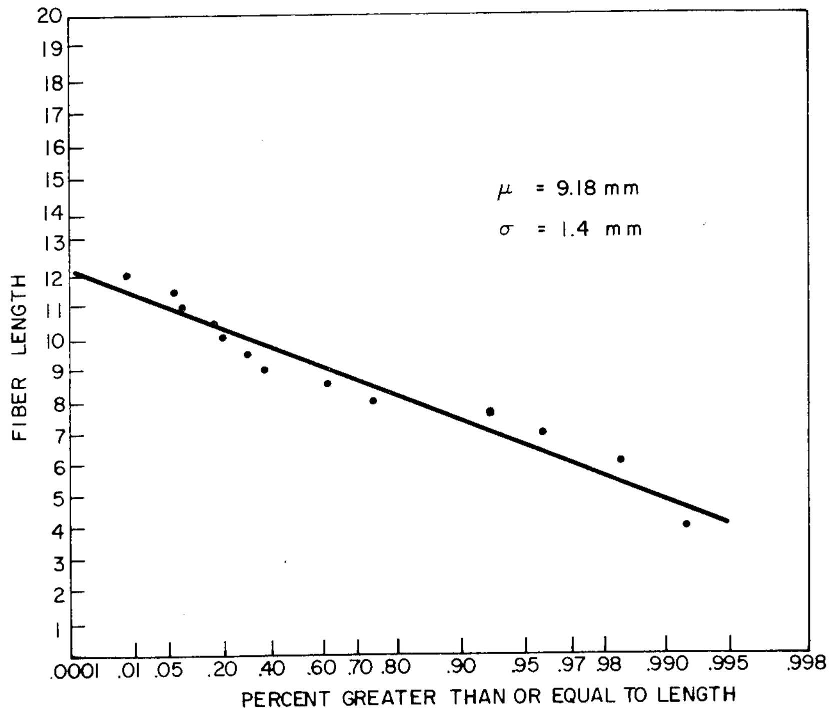

Figure 13.- The fiber length spectrum for 9 and 10.8 mm fibers combined, plotted on extreme value paper.

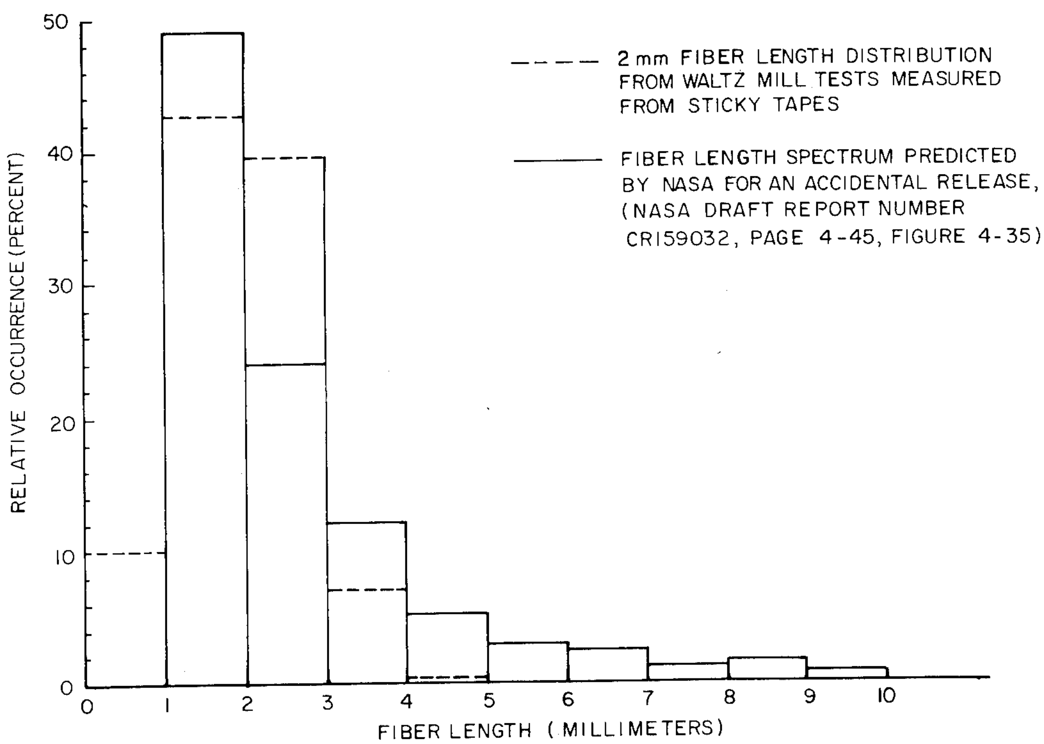

Figure 14.- Comparison of 2 mm fiber length distribution with the expected length distribution of an actual release.

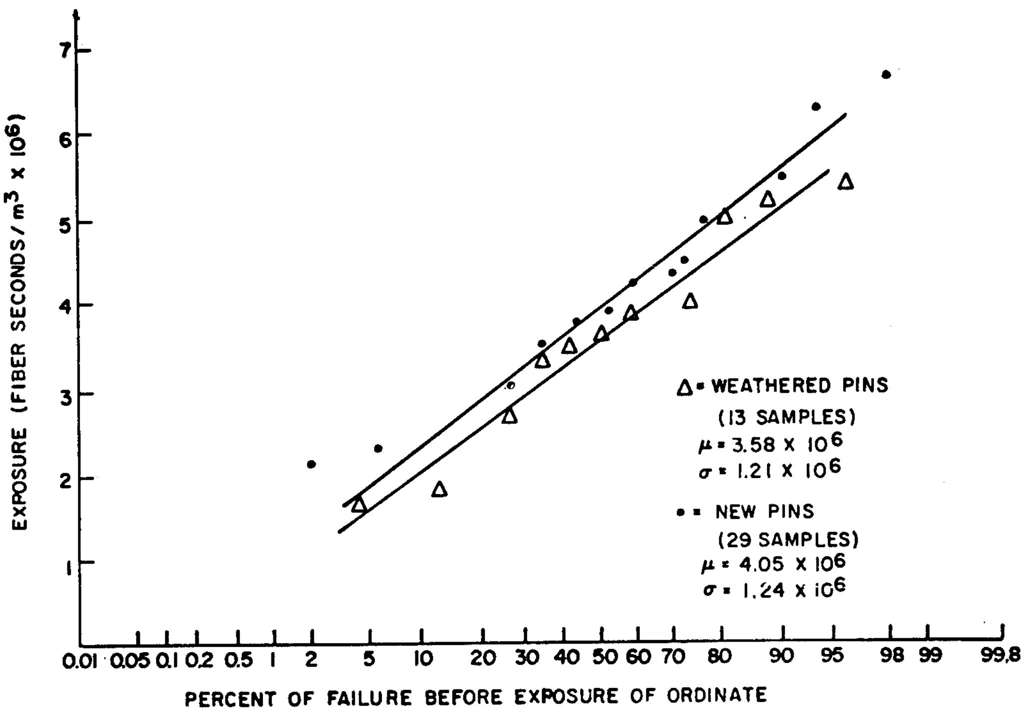

Figure 15.- Exposure to flashover for weathered versus non-weathered 7.5 kV pin insulators with 9 mm fibers.

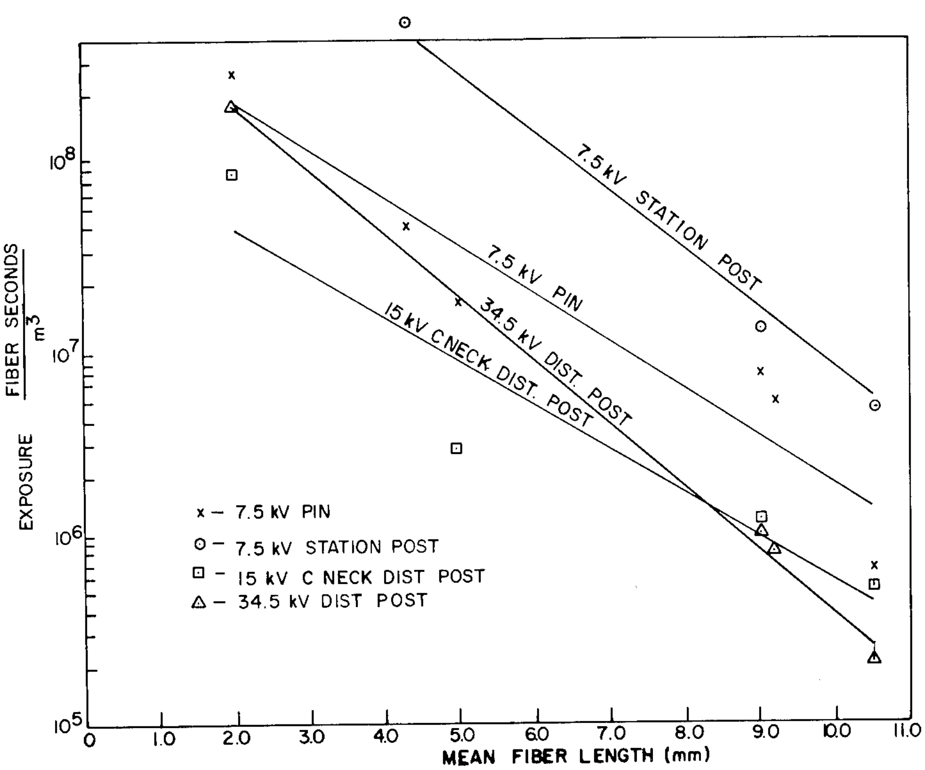

Figure 16.- Trend relating flashover exposure to mean fiber length plotted on semilog paper.

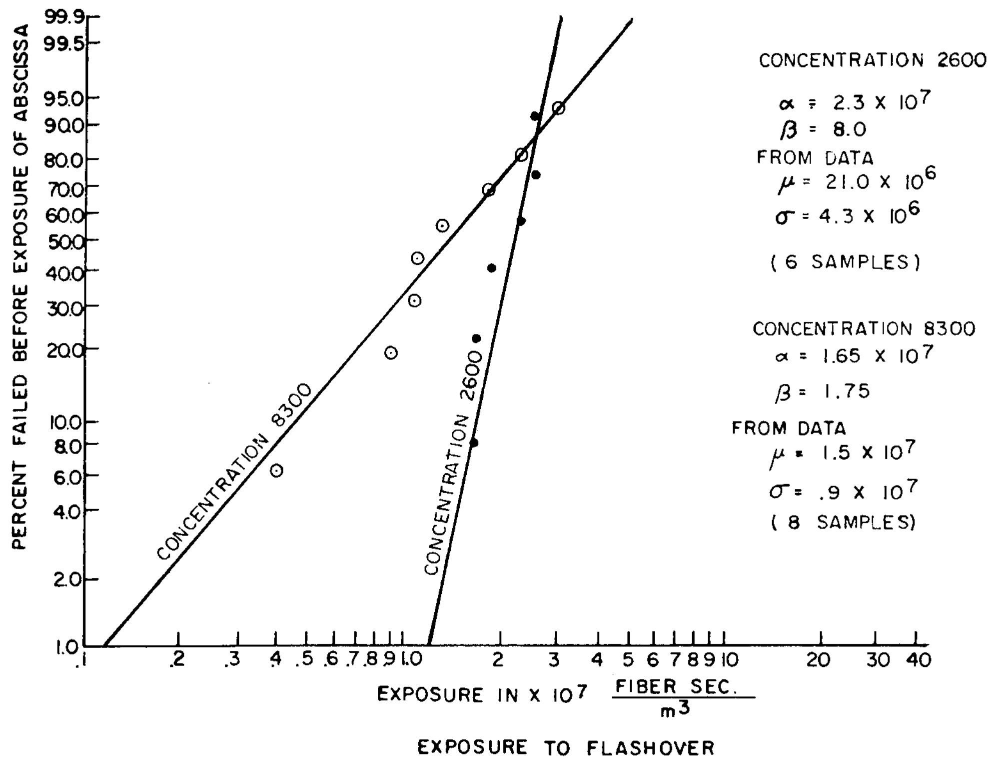

Figure 17.- Exposure to flashover for 7.5 kV pin, combined 4.3 and 9 mm fibers, concentration.

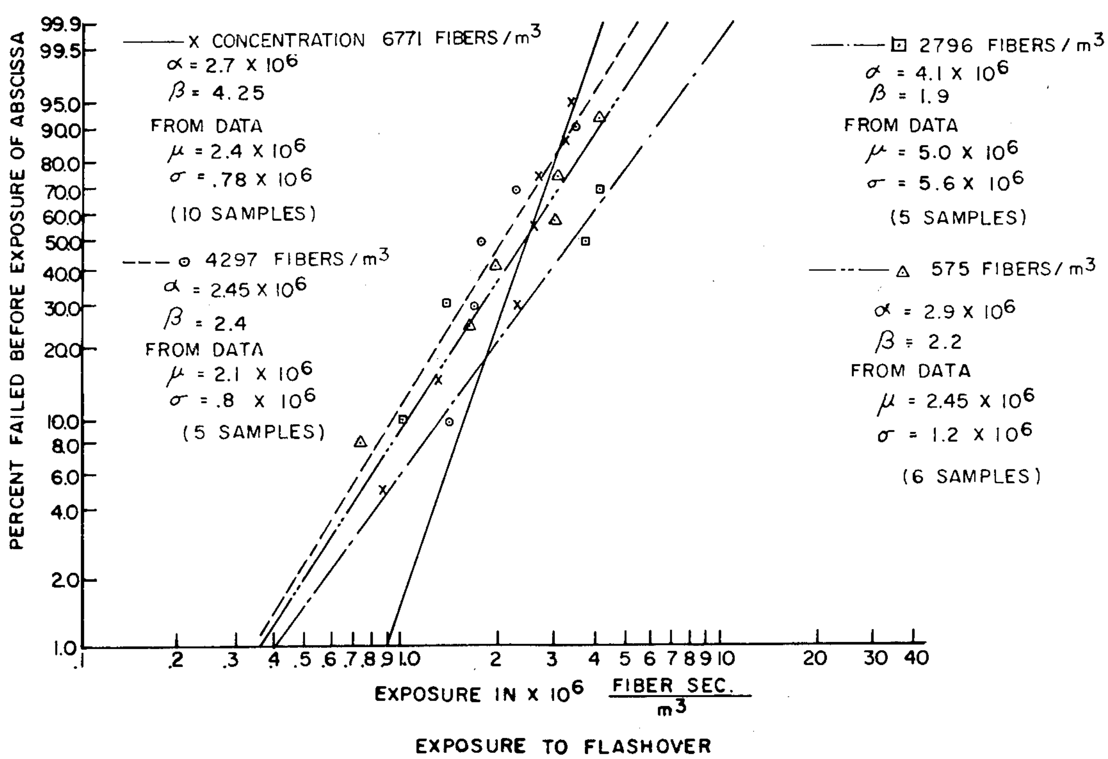

Figure 18.- Exposure to flashover for 15 kV distribution post, combined 4.3 and 9 mm fibers, concentration.

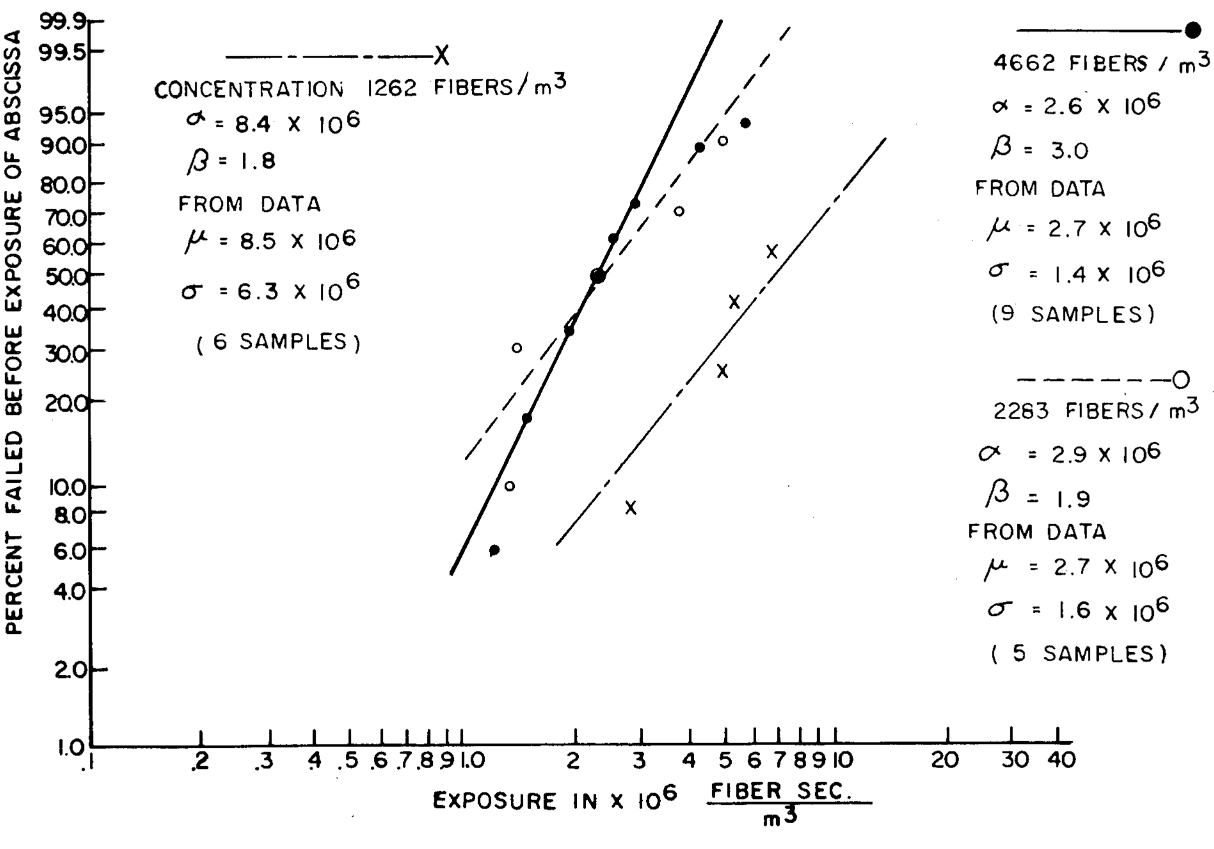

Figure 19.- Exposure to flashover for vertical 7.5 kV station post, 10.8 mm fibers concentration.

EFFECTS OF CARBON FIBERS ON CONSUMER PRODUCTS

R. A. Wise and C. D. Lovett
National Bureau of Standards

INTRODUCTION

In order to evaluate the potential effects of carbon fibers on consumer products, the Center for Consumer Product Technology of the National Bureau of Standards (NBS) was called upon due to its familiarity with the design, construction, operation and features of major and small consumer appliances. The NBS role was to develop the basic data needed to estimate hazard and fault susceptibility. The calculation of the possibility of hazards and faults actually occurring was not included in the NBS study nor were any actual fiber exposure tests made by NBS. Home entertainment (electronic) and vehicular products were excluded.

The information we are about to present covers work done by NBS under contract[1] to NASA which will be detailed in a report to be delivered to NASA titled: A Study of the Effects of Carbon Fibers on Home Appliances[2].

R. A. Wise will discuss the test and analytical methods used and C. D. Lovett will then describe the method used to select products and the results of the NBS activity.

Once the selection of appliances to be evaluated was made, typical models were purchased, and each was disassembled and thoroughly evaluated for hazard and fault potential. Follow on activity expanded the evaluated products list with particular emphasis on gas and oil fired heating products.

METHODOLOGY

Hazard Analysis

Of the hazards considered, fire, flood, physical harm, explosion, and electrical shock, only the latter was found to be a possible occurrence particularly related to carbon fibers.

[1] *Order no. L-81246A.*

[2] *Lovett, Denver; and Wise, Robert A.: A Study of the Effects of Carbon Fibers on Home Appliances, National Bureau of Standards IR 79-1952, December 17, 1979.*

Fires due to arcing or heat from the fiber seem unlikely due to the low maximum wattage that fibers can dissipate, but this was not experimentally verified. Shock possibilities were considered for four classes of product:

1. 240 volt, direct wired
2. 120 volt, direct wired
3. 120 volt, 3 wire, plug-in
4. 120 volt, 2 wire, plug-in

Although the first three categories present no shock hazard if the appliances are manufactured and installed correctly and the electrical distribution system is correct, all categories were analyzed due to the possibility of an electrical ground connection being disconnected or of a three wire grounded plug being defeated. Since no current flows when a carbon fiber makes a connection between an electrical conductor and an ungrounded touchable conductive part of an appliance, the fiber will not burn out; and, since fibers are low enough in resistance to allow a current to flow that is large enough to cause a sensible shock, all non-insulated electrical conductors were examined. First determined was the distance of exposed electrical conductive parts (mostly terminals, frequently referred to as nodes) from any touchable conductive surface. If the distance was less than 20 mm a possible hazard was considered to exist. The 20 mm was selected on the assumption that fibers longer than 20 mm are not likely to find their way into home appliances. The exception to a simple distance measurement of uninsulated electrical connections was with open wire heaters. Such designs were evaluated by measuring the length of the heater wire or coil that was less than 20 mm from the chassis.

All potentially hazardous locations were then evaluated as to their enclosure (restriction to entrance of fibers), insulation of the nearby grounded surface (paint or enamel), air circulation, and whether the circuit was electrically energized all of the time or only when switched on. On permanently installed appliances only the ungrounded electrical parts (those not connected to the neutral incoming power line) were considered potentially hazardous. However, plug-in appliances could be connected with either input wire at above ground potential so all exposed conductors were evaluated for such appliances.

Figure 1 shows a simplified schematic diagram of an appliance. The load "L" might be considered as a single device or a very complex assembly of electrical controls and operators. In any case, it can be seen that with an ungrounded chassis, line voltage from the chassis to ground measured at "V" could result from a fiber connection anywhere along the electrical circuit such as at "A", "B", or "C". These would result in an electrical shock if a person located at "V" touched the chassis at the same time as he touched a nearby grounded conductor. All three connectors are affected by the polarity of the plug-in connections and the connection at "B" is affected by the setting of the on-off switch.

Fault Analysis

A fault was considered to be any effect on the performance of an appliance which would result in a complaint or require service action. Figure 2 is a simplified electrical schematic showing some typical electrical circuits. It can be seen that fibers across 240 or 120 volt components such as heaters "H," motors "M," etc. can have no effect since they only constitute a very small additional load on the power supply and will quickly burn out. Recognizing the very low current carrying capacity of fibers, fibers across switch connections "S" are generally no problem. The only possible faults that can arise are those shown at locations 1 and 2. Fibers located at these positions where a switch operates a very low current device such as a timer motor "T" or relay "K," (under 10 watts) could cause the timer to run or the relay to close. Very few cases were found where such conditions exist, and these were tested with a carbon fiber simulator. This is an electronic device developed at the Langley Research Center and supplied to NBS to simulate fibers of various resistances and their burnout characteristics. Electronic controls have recently begun to replace electro-mechanical controls on a few consumer products so an attempt was made to determine the effect of fibers on these electronic controls through circuit analysis. The number of potential problems that could arise was very high, and actual exposure testing in a chamber was the only evaluation possible. However, all such products had their electronic parts well enclosed; so the likelihood of a fiber falling on such circuits is extremely remote.

RESULTS OF THE STUDY

Market Statistics

An analysis of market statistics resulted in estimates of the total depreciated 1977 dollar value in U.S. homes of $50 billion for major appliances and $10 billion for small appliances. Using the total depreciated dollar value, appliance categories accounting for 80% of the estimated total values were identified and subsequently 59 models representative of these categories were selected. These selected models include specific models that are (1) representative of appliances in the field (2) representative of changing technology in appliances and (3) appliances that have rapid growth trends. In addition to these 59 models other household consumer products and equipment[2] were examined to determine if carbon fibers might have an adverse effect.

Faults

Forty-seven of the 59 appliances were nonelectronic and were considered amenable to evaluation by probe testing and analysis. The evaluation determined the potential faults and hazards that could occur if fibers should enter the electrical circuits of these selected appliances. In these 47 appliances examined, 23 potential faults were detected. Twenty of these faults were of minor consequence, such as indicator lights operating when not expected. The remaining 3 faults could result in possible false cycles.

[1]*Major appliances included: refrigerators, clothes washers, electric ranges, freezers, dishwashers, clothes dryers, microwave ovens.*

Small appliances included: vacuum cleaners, irons, toasters, fry pans, coffee makers, bed covers, blenders, can openers.

[2]*Other products and equipment included: fans, drills, gas ranges, gas clothes dryers, gas furnaces, automatic flue dampers, furnace controls, garage door openers.*

Hazards

As explained earlier, an electrical shock depends on several conditions occurring at the same time as the user physically interfaces with the appliance. Our evaluation of electrical shock did not attempt to determine whether the interaction of the user provided the right set of conditions to complete a circuit between a touchable surface and an available ground. Rather, the evaluation counted the number of exposed nodes located close enough to a conductive surface for fibers to bridge the gaps, thus creating circuits which would allow a voltage to exist on a touchable surface.

Figure 3 shows that these 47 nonelectronic appliances contained approximately 1000 exposed nodes. A group of 947 nodes represent low likelihood of hazards because of the following restrictive conditions.

1. 85% of the fibers are expected to have lengths less than 5 mm so very high exposure will be required for fibers to bridge the gaps between any one of 802 nodes and their respective adjacent surfaces.

2. Coated surfaces adjacent to 40 nodes provide insulation.

3. A group of 105 nodes are well protected by their location in nearly closed compartments.

The remaining 53 nodes can be divided into two groups. The first group of 37 nodes is found in 19 major appliances. In these major appliances the possibility of a hazard depends upon the integrity of the ground system. If the ground system is intact, the likelihood of hazard occurring is very low. The second group of 16 nodes was found in 9 small appliances which have no provision for grounding. Figure 4 shows nine small appliance models and the number of potentially hazardous nodes.

Appliance Ground System

Plug-receptacle compatibility for 3-wire plug-in appliances depends on the availability of 3-contact household receptacles which are grounded. If plug-receptacle compatibility could be assured for all major appliances, then all potentially hazardous nodes would be confined to small appliances. Since this is not always the case, we identified those appliances for which plug-receptacle compatibility is assured and those appliances for which plug-receptacle compatibility is questionable. These major appliances and the corresponding number of potentially hazardous

nodes are shown in Figure 5. For example, clothes dryers, ranges and dishwashers contained 17 of the 37 hazardous nodes within this group of major appliances. Since clothes dryers and ranges are 3 wire, 240 volt appliances, their special 3 wire plugs will always be provided with compatible 3 wire receptacles, or they will be directly wired. Also, since most dishwashers are directly wired to their supply circuits, ground integrity is likely. The remaining ground system uncertainty is in 120 volt, 3 wire appliances consisting of four clothes washers which contain 13 hazardous nodes and 2 microwave ovens which contain seven hazardous nodes.

After completing the main program of consumer product analysis, several additional products were evaluated. Gas or oil furnace flame sensors of the photocell type were felt to be particularly susceptible, so several were purchased and evaluated analytically and with the carbon fiber simulator.

This extended study showed that the gas fueled appliance hazard possibilities were essentially the same as the electric counterpart designs and the electric shock hazard potential in furnaces is near zero due to the high probability that the electrical system and cabinetry are well grounded. The only possible fault-hazard condition was found to be in an intermittent ignition type furnace control which could permit fuel to flow with the flame out and igniter off. This fault is an extremely remote possibility since a fiber would have to arrive after the burner had started and then would require a flame-out to occur before the furnace had gone into its next off cycle. After the "off" cycle a fiber in this location would prevent the burner motor or gas valve from operating at the next "on" cycle.

The occurrence of any potential hazard depends on the carbon fiber transfer function into appliance compartments. If the transfer is small, the possibility of occurrence is remote. NBS did not evaluate transfer functions for appliances.

Appliances Recommended for Chamber Testing

Sixteen of the appliances were not amenable to probe testing and analysis for quantifying potential faults and hazards, the reason being:

1. Some of the models contained electronic controls. Evaluation of these electronic control models indicated that potential faults were too numerous to quantify.

2. Toaster, toaster-ovens, heaters and hand irons contain uninsulated stiff wire or sheet metal conductors. Because of the varied configuration, and the large number of possible interconnections, it is not practical to analytically evaluate the hazard potential of these products.

3. Portable room heaters, toasters, and clothes dryers contain uninsulated heater wires which are exposed to various amounts of fan and convection forced air. These products also have numerous possibilities for fiber connections.

Eleven models were recommended for chamber testing (See figure 6). Nine, because they were representative of those not amenable to probe testing and analysis. Two other products, a clothes dryer and a dishwasher, were chosen as representative appliances to quantify the fiber exposure required to cause a fault or a hazard as an indication of the vulnerability of these appliance categories and others of similar construction.

CONCLUSIONS

A. Few products were found to be susceptible to faults. For nonelectronic appliances most faults were of minor consequences. However, for electronic appliances our analysis indicated that the fault possibilities were too numerous to analyze. Therefore, these appliances were recommended for chamber testing. A review of carbon fiber chamber test data from other NASA contractors revealed no faults in those appliances recommended for chamber testing.

B. Our analysis showed that carbon fiber generated circuits could create many potential hazards in many appliances. However, the number of potential hazards is reduced by (1) increased spacing to fiber length ratio (2) coated surfaces and (3) the availability of correctly grounded receptacles. A review of the carbon fiber exposure data for those appliances recommended for chamber testing, in most cases, confirmed our prediction of hazards for these appliances.

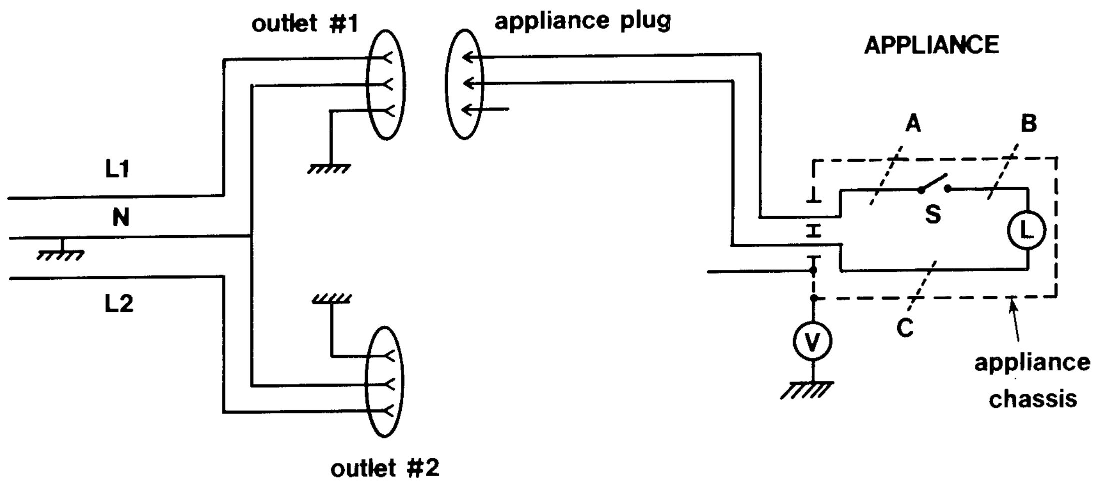

Figure 1.- Hazard analysis.

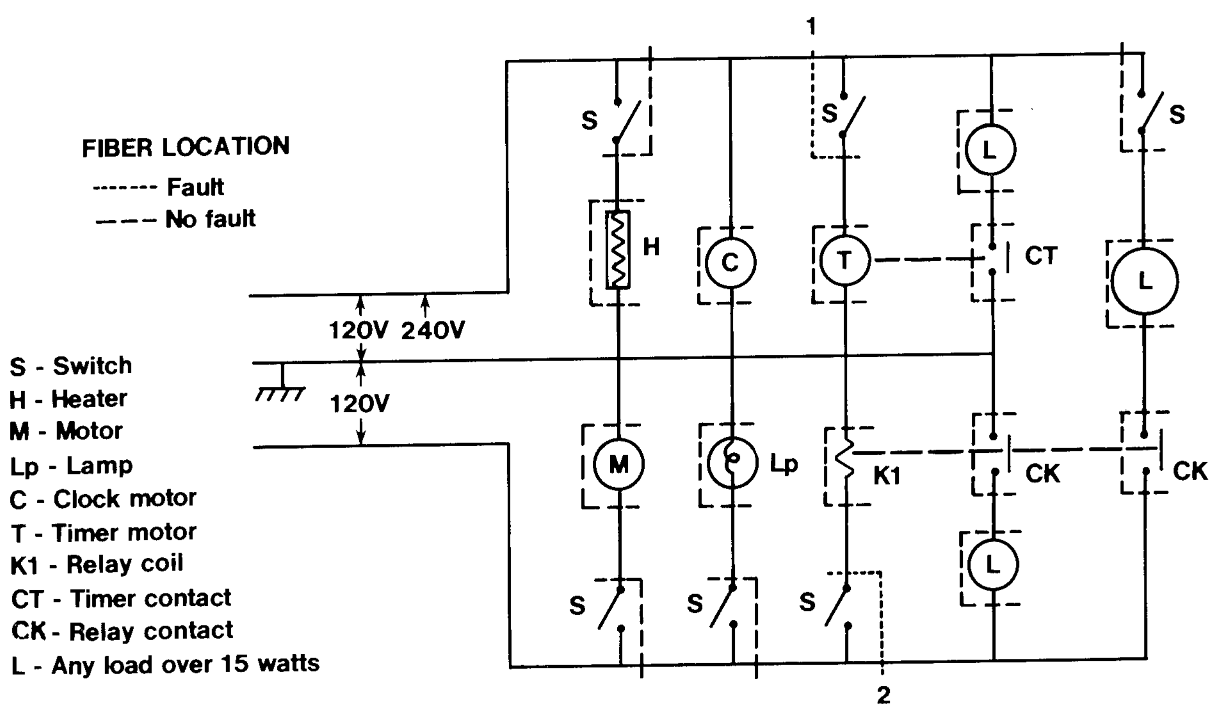

Figure 2.- Fault analysis.

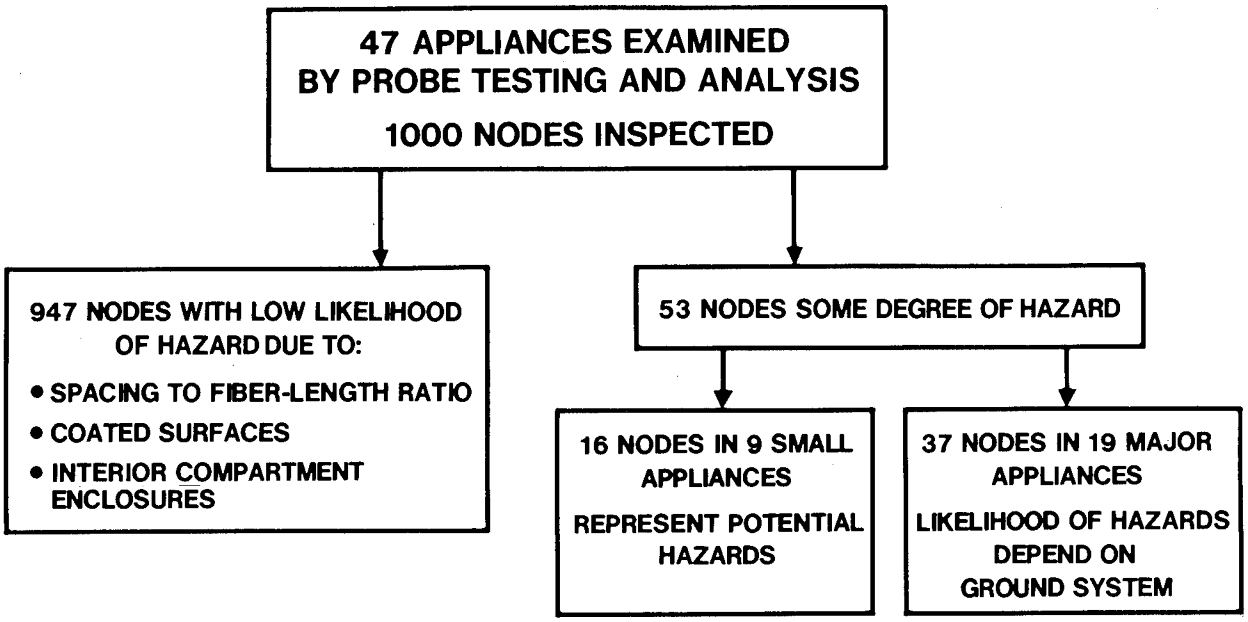

Figure 3.- Appliance probe test summary.

PRODUCT CATEGORY	NUMBER EXAMINED	NUMBER OF HAZARDOUS NODES
VACUUM CLEANER	3	4
* FOOD MIXER	3	4
* PORTABLE HEATER	3	8
TOTALS	9	16

*Hazards in these appliances were verified by carbon fiber chamber tests sponsored by NASA-Langley

Figure 4.- Small appliances with potential hazards.

PRODUCT CATEGORY	NUMBER EXAMINED	NUMBER OF HAZARDOUS NODES
CLOTHES WASHER	4	13
RANGE*	2	1
DISHWASHER*	3	5
CLOTHES DRYER*	4	11
MICROWAVE OVEN	2	7
TOTALS	15	37

* Ground system violation highly unlikely for these appliances

Figure 5.- Major appliances with potential hazards.

APPLIANCE CATEGORY	NUMBER OF UNITS
CLOTHES DRYER	2
DISHWASHER	1
TOASTER	1
TOASTER OVEN	1
HAND IRON	1
SMOKE DETECTOR	2
HEATER	1
MICROWAVE OVEN	2
TOTAL	11

Figure 6.- Appliances recommended for carbon fiber chamber test.

RISK ASSESSMENT OF CARBON FIBER
COMPOSITE IN SURFACE TRANSPORTATION

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SUMMARY

The vulnerability of surface transportation to airborne carbon fibers and the national risk associated with the potential use of carbon fibers in the surface transportation system have been evaluated. Airborne carbon fibers may cause failure rates in surface transportation of less than one per year by 1995. The national risk resulting from the use of carbon fibers in the surface transportation system is projected to be an annual dollar loss on the order of $6,000.

INTRODUCTION

This report describes the status of the Department of Transportation Carbon Fiber Project which addresses the surface transportation portion of the coordinated Federal Government Carbon Fiber Action Plan presented in reference 1.

The DOT responsibilities are to assess the vulnerability of surface transportation to airborne carbon fibers and to assess the national risk due to carbon fibers released from surface transportation.

The project was divided into the following five tasks:

(1) To estimate the quantities of carbon fiber that will be used in the surface transportation system by 1995.

(2) To estimate the frequency and location of surface transportation system fire incidents.

(3) To estimate through laboratory tests the size and quantity of carbon fibers released by surface transportation fires.

(4) To estimate the vulnerability of the surface transportation system to airborne carbon fibers.

(5) To estimate the national risk from carbon fibers released in surface transportation incidents.

CARBON FIBER COMPOSITE USAGE

An estimate of the expected carbon fiber quantity and matrix composition in surface transportation was developed by DOT from a review of the existing literature, the Department of Commerce survey conducted in 1979 (presented in a preceding paper by Donald Parsons reference 2) and several independent inquiries to carbon fiber suppliers and users. This effort further established that the only prospective use of carbon fibers in the transportation system would be in automobiles, light trucks and heavy trucks. The DOT estimates place the total carbon fiber usage in surface transportation in 1995 at less than $5X10^7$ kg. The estimate DOT chose for its risk assessment was 2 kg in cars and light trucks and 15 kg in heavy trucks. Table 1 shows the actual DOT usage estimates and the expected matrix composition.

TRANSPORTATION FIRES

The exposure of carbon fiber composite materials to a severe fire is the principal mechanism for the release of carbon fibers. Table 2 shows a summary of surface transportation vehicle fires estimated by the U.S. Fire Administration (USFA) and a projection of total vehicle fires estimated by the National Fire Protection Association (NFPA). As stated previously, nearly all carbon fiber materials used in surface transportation will be found in cars and trucks. Therefore, car and truck fires are of principal concern in a study of potential carbon fiber release incidents.

The fire data inputs needed for the risk assessment consist of an estimate of the frequency and geographic location of the fire and portion of the vehicle involved. Fire frequency can be found in Table 2 but the above data sources have little information on geographic location.

The Highway Safety Research Institute at the University of Michigan has collected information from fire department records on automobile fires in the state of Michigan for the two year period from 1976-1977. This data is collected by county and it was possible to establish a correlation between the annual automobile fires per county and county population. The correlation (a correlation coefficient of 0.97) indicated that the urban car is more susceptible to fire as most automobile fires occur in urban areas where the vehicle population density is highest.

The other details of the automobile fire scenario which are important to fiber release are the severity of the fire and its location on the vehicle. The fire location on the vehicle was important to determine which of the composite materials were exposed to the fire. The vehicle fires were classified by one of the following scenarios: engine small, engine severe, passenger compartment small, passenger compartment severe and total conflagration. Severe fires were defined as the only fires that will release carbon fibers. Since no carbon fibers are expected to be used in the passenger compartment,

only severe engine fires and total vehicle conflagration fires will release fibers. Roughly one-third of the car and truck fires fall into these two release scenarios. This estimate is based on an analysis of the passenger vehicle dollar loss statistics for fires and is published by the California State Fire Marshall.

LABORATORY TESTS

All the laboratory and field test data available for the release by fire of carbon fibers from composite samples were on aerospace-grade, epoxy based materials, usually with post-fire impact or explosion. It was felt that this data was not an accurate representation of the fiber release expected from automotive-grade composite. Automotive composites are expected to be based on a matrix of vinyl ester or polyester and glass fibers blended with carbon fibers.

DOT developed a series of laboratory tests to measure carbon fiber release from automotive-type composites. The tests were designed to evaluate carbon fiber release under conditions which simulated automobile fires, namely high and low radiant heat flux with an 1800°C propane/air flame, fuel rich or fuel lean. The burning time was 10 minutes and there was no post-fire impact or explosion. Prior to the execution of the program by NASA-Ames and its contractor, Scientific Services, Inc., users and suppliers of the carbon fiber materials were asked to review and comment on the test program.

The results of this test program are briefly summarized in Table 3. The quantities of carbon fiber released were found to be sensitive to the test condition but not to the matrix resin. Depending on the test conditions, the basic results from this test program were an average carbon fiber release over the range from 0.003 percent to 0.06 percent of the composite carbon fiber weight. Ninety-nine percent of all carbon fibers released were less than three millimeters in length. Fibers of this length in the quantities released from the test are unlikely to cause electrical failures in any individual incident.

VULNERABILITY OF SURFACE TRANSPORTATION

Surface transportation systems have been designed to operate reliably and safely in an environment of dust, oil, salt spray and vandalism. These system requirements produce a system design which is not easily affected by a carbon fiber hazard. From the above analysis of the Michigan data, it was determined that most of the carbon fiber exposure will be in the vicinity of the urban roadway system. Since very little of this urban roadway system interfaces with the waterway transportation system, the vulnerability of water transportation was not evaluated beyond a brief qualitative determination that it would be relatively invulnerable to the few carbon fibers to which it would be exposed. The remaining modes bore the brunt of the exposure and were thoroughly evaluated.

The method used to estimate the vulnerability of a surface transportation system was to divide the system into subsystems and, if necessary, components to a point where the vulnerability of the subsystem or component could be estimated from vulnerability data published by NASA and DOD. The effects of the subsystem failure are then classified as safety, performance or convenience failures. A safety failure occurs when there is a significant loss of system safety; a performance failure occurs when there is a significant loss in system performance; and a convenience failure occurs when there is a significant loss in the perceived comfort or convenience by the passengers or crew. This analysis as applied to the passenger car is seen in Table 4. In the vulnerability column, V indicates a vulnerability less than 10^8 fiber seconds/meter^3; P means that the equipment is sealed against fiber penetration; and C means that the current and voltage ranges are insensitive to carbon fibers. For example, the alternator will burn out any carbon fibers which penetrate it, the voltage regulator is potted in plastic, but carbon fibers can interface with the operation of the radio. Table 4 shows that only radios may be vulnerable to carbon fibers. Tests have shown that an automobile radio has a vulnerability greater than 10^8 fiber seconds/meter^3. The passenger car, thus, is effectively not vulnerable.

Similar analyses have shown that both the truck and the bus are also not vulnerable. Traffic signal systems are housed in sealed enclosures which will exclude carbon fibers so that they too are not vulnerable. The net result is that the highway system is not vulnerable to airborne carbon fibers.

Electrified rail systems were analyzed by dividing them into carborne, wayside, electric substation and signal subsystems. The result of this analysis is shown in Table 5. These vulnerabilities, with the exception of the signal system, all represent system failures. Most of the failures are monetary and are likely to require no maintenance or repair, e.g., a flashover at a third-rail insulator. The vulnerability of the vehicle is shown for both a single car and a six-car train. The vulnerability of the six-car train assumes that the traction motors must fail on more than three cars for the train to fail. This is a reasonable assumption since the performance of a train is not significantly affected until more than half its cars lose their traction motors. It is, in fact, common for transit systems to have failed cars in their trains.

RISK ASSESSMENT

A typical surface transportation release incident can be characterized as a release of 20 grams of single fibers, less than 3 mm long; most of the fibers fall out within a kilometer of the source, and the incident frequency is correlated with population. It is estimated that there will be 100,000 such incidents a year. Preliminary calculations show that the probability that there is any damage from an individual incident is very low. As discussed in reference 3, the case where there are a large number of incidents with a low probability of damage by an individual incident is best modeled analytically

by Poisson statistics.

The national risk due to fibers released by surface transportation was computed by the NASA Langley Research Center contractor Arthur D. Little Inc. under a reimbursable agreement from DOT to NASA. A brief review of their method is as follows:

The number of release incidents and number of carbon fibers released each year is estimated for each of 3,000 counties in the U.S.

The number of equipments, along with their associated vulnerabilities and failure costs, is tabulated for these counties.

The losses for the individual counties are then calculated and summed to determine the national risk.

The result of this calculation was a projected annual national dollar loss, associated with the use of carbon fibers in surface transportation, on the order of $6,000 per year.

CONCLUSIONS

The vulnerability of surface transportation to airborne carbon fibers is very low. The risk of failure is less than one a year at the carbon fiber hazard level predicted for the year 1995. Similarly, the national risk due to this hazard is very low. The annual dollar or loss estimate is on the order of $6,000 a year. Because of this small vulnerability and risk, the DOT carbon fiber program will conclude early in FY 80.

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TABLE 1

DEPARTMENT OF TRANSPORTATION CF USAGE ESTIMATES

Year	Average CF/Auto (KG)	Average CF/ Heavy Truck (KG)
1990	0.5	1.0
1995	2.0	15.0

PROJECTED MATRIX COMPOSITION

RESIN	TYPE
Polyester	Graphite/Glass Hybird
Vinyl ester	Graphite/Glass Hybird

TABLE 2

TRANSPORTATION FIRES* (1977 - USFA)	
PASSENGER VEHICLES	325,000
FREIGHT ROAD VEHICLES	58,000
RAIL TRANS. VEHICLES	2,800
WATER TRANS. VESSEL	1,850
AIR TRANS. VEHICLE	550
HEAVY EQUIPMENT	7,000
SPECIAL VEHICLES	2,700
OTHER MOBILE PROPERTY	100
UNDETERMINED	62,000
TOTAL	460,000
NFPA EST.** TOTAL	490,000

*EST. BASED ON 26% SAMPLE OF U.S. POP. (8 STATES)

**BASED ON DATA FROM 4% OF FIRE DEPTS. (IN 50 STATES)

TABLE 3

TEST RESULTS

	HIGH RADIANT, FUEL LEAN	LOW RADIANT, FUEL RICH
AVERAGE PERCENT RELEASED	.003%	.06%
AVERAGE MEDIAN FIBER LENGTH	0.1 MM	0.9 MM

TABLE 4

PASSENGER CAR ELECTRICAL SYSTEMS

SUBSYSTEM/COMPONENT	VULNERABILITY	EFFECT
ENGINE:		
IGNITION	P	PERFORMANCE
ALTERNATOR	C	CONVENIENCE
VOLTAGE REGULATOR	P	CONVENIENCE
BATTERY	C	PERFORMANCE
STARTER	C	PERFORMANCE
CHASSIS:		
HEATER	C	CONVENIENCE
WINDOW DEFOGGER	C	CONVENIENCE
WIPER/WASHER	P	SAFETY
FUEL:		
PUMP	P	PERFORMANCE
EMISSION CONTROLS	P	PERFORMANCE
INJECTION	P	PERFORMANCE
LIGHTING:		
HEADLIGHT	C	PERFORMANCE
TAIL LIGHT	C	SAFETY
BRAKE	C	SAFETY
TURN	C	SAFETY
INTERIOR	P	CONVENIENCE
ACCESSORIES:		
CLOCK	P	CONVENIENCE
ENTERTAINMENT - RADIO	V	CONVENIENCE
CB RADIO	V	CONVENIENCE
DIGITAL INST.	P	CONVENIENCE

V - POTENTIALLY VULNERABLE.

P - PROTECTED FROM PENETRATION OF CARBON FIBER.

C - CURRENT OR VOLTAGE IN A RANGE NOT SENSITIVE TO CARBON FIBER.

TABLE 5

VULNERABILITY OF AN ELECTRIFIED RAIL SYSTEM

VEHICLE	FIBER SEC/METER^3
SINGLE CAR	1.5×10^5
6 CAR TRAIN	1.5×10^9
WAYSIDE POWER	1.8×10^6
SUBSTATION	3.5×10^8
SIGNAL SYSTEM	6×10^9

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16. Abstract

Carbon fibers used in structural composites are light weight and electrically conductive. When carbon fiber composites are burned, such as may occur in an aircraft crash fire, the light-weight conductive carbon fibers may be released from the composite and become airborne. Settlement of the conductive fibers on electrical and electronic equipment may cause malfunctions in the equipment.

The results of an assessment of the risks associated with the use of carbon fiber composites in civil aircraft, projected for the year 1993, are presented. An assessment of the need for protection of civil aircraft equipment from fire-released carbon fibers is also presented. The assessments are based on the results of test and analysis work conducted by NASA as part of the federal government's carbon fiber action plan. The status of work undertaken by other government agencies under the action plan is also presented.

The approach taken by NASA to assess the risks and the elements of the assessment are discussed, including estimates of the size and number of carbon fibers released from composites involved in civil aircraft crash fires, estimates of the downwind dissemination of the fibers, their penetration into buildings and equipment, and the vulnerability of electrical/electronic equipment to damage by the fibers.

17. Key Words (Suggested by Author(s))

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